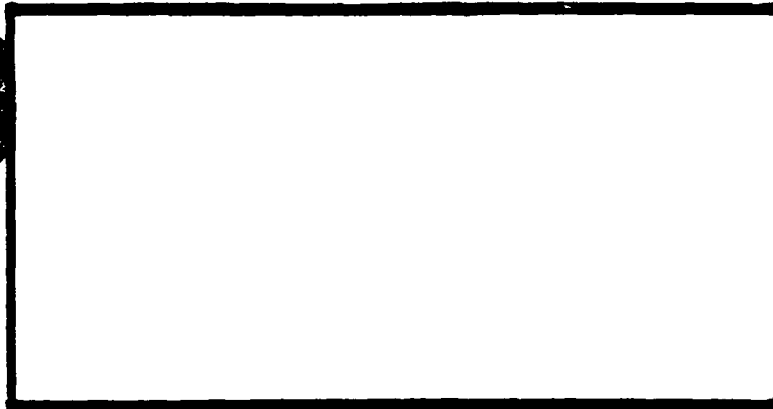


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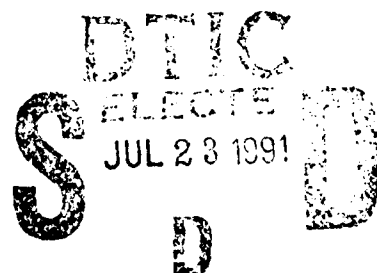
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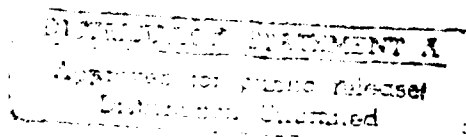
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**AGILITY: PRESENTATION AND FLIGHT TEST
METHODS FOR THE
OPERATIONAL FIGHTER PILOT**

THESIS

William R. Langdon
Captain, USAF
AFIT/GAE/ENY/91M-2



March 1991

M.S. Thesis

Agility: Presentation and Flight Test Methods
for the Operational Fighter Pilot

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This thesis develops both metrics and flight test techniques to measure agility. During development of both the agility metrics and the flight test techniques, previous work conducted by the agility community and the Flight Test Center at Edwards Air Force Base was used as a lessons learned tool to insure favorable results. Both simulator and flight testing was performed to validate the flight test techniques. During simulator testing several problems with the original flight test techniques were noted. Flight testing on the pitch agility flight test technique solved most of its problems but problems found during roll testing in the simulator were not flight tested. Flight testing was limited to pitch agility testing only due to time and resource constraints. Results from the flight test were impressive showing a significant advantage using post-stall agility in the A-37B aircraft. Up to 40 degrees of heading change was obtained in approximately one second. This turn rate exceeds all maximum instantaneous turn rates for current front line fighters. These results were analytically applied to 180 degree turn maneuvers and resulted in up to a 20% time savings from conventional turn methods. This will ultimately allow the fighter pilot to make an educated decision which flight condition is best to defeat a threat.

Thesis Advisor: Major (Dr.) Daniel Gleason

Adjunct Assistant Professor of Aerospace Engineering

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Agility Metrics and Flight
Test Techniques

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***AGILITY: PRESENTATION AND FLIGHT TEST
METHODS FOR THE
OPERATIONAL FIGHTER PILOT***

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautical Engineering

William R. Langdon, B.S.

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Preface

The purpose of this study was two-fold. First, to develop metrics that present the agility of fighter aircraft in an easy to understand format and are useful to the operational fighter pilot. Second, to develop valid and repeatable flight test techniques to measure the agility of an aircraft.

To develop the metrics, a study of past attempts to quantify agility are presented and new metrics developed from their shortcomings. Flight test techniques from previous testing were used to develop new techniques that are relatively easy to fly and produce repeatable results. Both simulator and flight testing were performed to validate the flight test techniques. The results of this study provided significant findings in the agility field and should be applied to other types of aircraft to build an agility data base that is useful to the entire fighter community.

During the research and development part of this effort I would like to thank Mr. Tom Cord for providing his expertise on the field of agility. Without his initial help, this study would have taken at least twice the time to complete. I would also like to thank my wife, Tammy, for her understanding and patience over the last two and a half years.

William R. Langdon

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Notation

AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AOA	angle of attack
C_{Lmax}	maximum coefficient of lift
CRT	cathode ray tube
DAS	data acquisition system
DT	Distance and Time
deg	degrees
ECM	electronic counter measures
FRL	fuselage reference line
FTT	flight test technique
H_c	pressure altitude
HSI	Horizontal Situation Indicator
HUD	Heads-up Display
in	inches
IRCM	infrared counter measures
KCAS	knots calibrated airspeed
KIAS	knots indicated airspeed
KTS	nautical miles per hour
LAMARS	Large Amplitude Multimode Aerospace Research Simulator
LANTIRN	Low Altitude Night Time Infrared Navigation
MAC	mean aerodynamic chord
mil	miliradian
N_z	normal load factor
PCM	pulse code modulation
P_s	specific excess power
USAFTPS	United States Air Force Test Pilot School

Abstract

The purpose of this study was two-fold. First, to develop metrics that present the agility of fighter aircraft in an easy to understand format that is useful to the operational fighter pilot. Second, to develop valid and repeatable flight test techniques to measure the agility of an aircraft.

During development of both the agility metrics and the flight test techniques, previous work conducted by the agility community and the Flight Test Center at Edwards Air Force Base was used as a lessons learned tool to insure the results would be favorable. Both simulator and flight testing were performed to validate the flight test techniques.

During simulator testing, several problems with the pitch agility flight test technique were noted. Repeatability in the initial procedure was almost non-existent. The problems found at that time were corrected during the flight test portion of testing. Simulator work also raised some questions about the roll agility technique. Further testing was not performed on this procedure due to the limited scope of the flight test. Whether the problems found actually showed agility problems with the simulator configuration or problems with the flight test technique itself are not known.

Flight testing was limited to pitch agility only due to time and resource constraints. Results from the flight test were impressive showing a significant

advantage using post-stall agility in the A-37B. Angular reserve (the maximum heading change the aircraft can generate post-stall before slowing to a turn rate equal to or less than the maximum pre-stall turn rate) produced results of up to 40 degrees of heading change in approximately one second. This turn rate exceeds all maximum instantaneous turn rates for current front line fighters. When this was analytically applied to a tactical maneuver consisting of a 180 degree turn followed by tracking the nose of the aircraft for one second, time savings of up to 20% were obtained. This type of savings would allow a pilot to obtain the first shot in a tactical engagement. This flight test technique wasn't actually flown. The technique should be flown to verify the repeatability and accuracy of the analytical results.

While these results were tied directly to the A-37B aircraft, other aircraft should be tested to insure the flight test techniques developed are valid and repeatable for all types of aircraft. Agility data for all aircraft should be gathered in the format presented in this study to allow engineers, pilots and threat analysts to compare all fighter aircraft. This will ultimately allow the fighter pilot to make an educated decision as to what flight condition is the best to defeat a threat.

I. Introduction

Agility has become a hot topic in recent years and is at the forefront of technology in the design and production of new fighter aircraft. What has driven this interest, and is this really a new idea? To begin to look at agility, a clear definition of what is meant by 'agility' must be understood. Webster's defines agility as:

'The quality of being marked by ready ability to move with quick, easy grace; mentally quick and resourceful'

This definition, in general, is very straightforward, but when applied to aircraft it has caused heated discussions. One of the major questions posed is whether agility is separate from maneuverability. In this work, agility related to aircraft will be defined using the title of 'functional agility'. The author's definition of functional agility will be:

The ability to maneuver an aircraft quickly and precisely to complete a specified task or function

Obviously this definition includes maneuverability as part of agility. In fact it is the quickness and the precision portion of the total aircraft maneuverability in performing a task that makes up functional agility. The remainder of the work presented here will focus on functional agility as defined above.

Is agility something new? If this topic were discussed with several designers and pilots, at various periods of time, from the inception of the aircraft, the answer would

be NO! The way current researchers look at agility is probably very different now than those of 10, 25 or even 50 years ago. What has caused this change? The answer to this question is advanced weapon systems.

The agility learning cycle seems to repeat itself during and after a major conflict. In World War I, highly maneuverable biplanes were developed for the pilot to be able to position himself behind the enemy and employ the gun as the primary (and only) weapon. In the years after World War I, the agility of the warplanes declined as new technology was introduced and speeds were increased. During World War II, the need for more agile aircraft became clear as our airplanes were no match for the Germans during the initial portion of the war. This led to the development of the P-51 Mustang which was extremely agile.

With the introduction of the jet age came much higher speeds and greater acceleration, but the maneuvering portion of agility declined. It wasn't until the Korean War that the F-86 was developed to fill in the agility gap. The one thing in common with all the aircraft mentioned previously is that they used the gun as the primary air-to-air weapon, therefore good agility was very crucial. After the Korean War, the infrared and radar missile became the weapon of choice in the air-to-air arena. Therefore, the maneuverability of the aircraft employing these weapons was not a crucial design factor. The problem that the designers did not plan for was the extremely low probability of kill that these initial missiles had, thus requiring the aircraft to maneuver to a so called "sweet spot" to employ the missiles. During Vietnam, the primary aircraft used in the air-to-air arena was the F-4. The way to

stay alive flying this aircraft was to keep excess speed and to use hit and run tactics. The amount of time spent in an engagement had to be minimized due to the possibility of a missile being shot at a highly predictable, slow-moving target. With the further development of "Hi-Tech" missiles, the ability to "point and shoot" became a reality. Therefore, the F-15 and F-16 were developed with this in mind. Both of these aircraft are extremely agile aircraft when flown at their best maneuvering airspeed, but as the speeds slow down the aircraft tend to get 'sluggish' and do not respond as well as one would like. The designers did not expect the pilots to fly in this regime due to the lessons learned during Vietnam. With the introduction of IRCM (Infrared Counter Measures) and ECM (Electronic Counter Measures) new problems began to arise. With these countermeasures employed, pilots could not maintain air superiority unless they could slow down and use the gun to obtain kills. The new stealth technology will also have a direct effect due to the inability to employ radar missiles prior to the visual engagement. All this points in one direction. System must be designed with all aspects of air combat in mind including the employment of the gun whether desired or not.

The ability to turn quicker, accelerate/decelerate faster and employ weapons before the adversary can employ theirs is the objective of any fighter pilot. To realize this, the ability to measure and design for greater agility must be present. Future aircraft must incorporate agility as well as weaponry into the design process, and before any tradeoffs are made, the implications which these tradeoffs pose without full weapon system capability must be considered. New weapons may come

and go but as the lessons show we always return to agility!

The next section will present a background of agility work to date and will show the reader the importance of this effort. In Chapter III new metrics will be developed to present the important aspects of agility as they relate to the operational fighter pilot. Chapter IV presents a development of flight test techniques to quantitatively measure the important agility parameters. Simulator procedures and results used to verify the validity and repeatability of the designed flight test techniques is provided in Chapters V and VI. Flight test procedures and results used to verify the pitch agility flight test techniques are presented in Chapters VII and VIII. Conclusions and recommendations for the entire work are summarized in Chapter IX.

II. Background

In the early days of flight, the comparison of aircraft or the measurement of their performance was done strictly by flying the aircraft and taking the pilots word that it was either acceptable, unacceptable or better than the other aircraft. As the years went by, flight test became a much more exact science. With the implementation of data acquisition systems, the performance of the aircraft could now be measured and ways of presenting the data were designed. Colonel John Boyd applied a metric that uses specific excess power (P_e) to determine the energy maneuverability of an aircraft at a specific flight condition. For many years P_e was used to compare aircraft and make educated assumptions how an aircraft will perform against an adversary aircraft. The problem with this method is that it only shows how the aircraft can perform at an instant in time and does not take into account what is happening subsequent to the beginning of the maneuver. It does not show the total airspeed loss or how much time is required for the aircraft to regain its airspeed. Even though these metrics do show instantaneous turn rate capability at a certain starting condition, they are also lacking in the ability to give a turn rate over a period of time or after a specific amount of heading change. The energy maneuverability concept uses the aircraft as a point mass rather than a rigid body and therefore does not take into account the ability of the aircraft to rotate around its lateral axis. The idea of this rigid body rotation is

what the current agility experts are banking on to give them an increase in agility in future fighter aircraft. This metric is also unable to show the ability of the aircraft to precisely position its nose on a specified point for a range of flight conditions. All these tasks previously mentioned are the parameters needed to differentiate which aircraft has the superior agility in the dogfight arena. To incorporate this into the present metric would be impossible, therefore new metrics to present these parameters in relation to time are needed. One point must be made clear. Developing this metric will not replace the traditional energy maneuverability plot, but will be used to supplement it.

The development of new metrics to present agility data is a challenge due to the wide variety of fields that can use this data. Engineers, pilots, and threat analysts are just a few of the people that can benefit from this information. The method of presentation is very important to the person using the data. While engineers may need some complicated parameter or intricate details to the metric they use, a pilot, most likely, will not be able to transfer these parameters into a physical meaning. The past energy maneuverability metric was readable, but took time to analyze and compare aircraft characteristics. Therefore, the young fighter pilot was exposed to these charts in his initial training in fighters but rarely used them in the operational world. USAF Weapons School graduates that were assigned to each unit usually had the task of deciphering the data and presenting it to the line pilots in an easily understandable format. The methods that will be developed in this work will use the basic concepts behind agility and attempt to present the data so that there is some

physical meaning. It will also present it so basically that an engineer can pull the intricate details from the data presentation. To begin to develop these metrics, an understanding of what a pilot thinks are physically important aspects of agility is required. Energy maneuverability metrics basically centered on an "energy" fight rather than an "angles" fight. The advanced weapon systems today require aircraft to use a "point and shoot" tactic over the traditional energy maintaining fight. That is not to say that energy is of no importance, because it is! But, in today's engagements, it is the author's opinion that the ability to trade the energy for nose pointing and tracking capability or rotating the aircraft's vulnerable cone¹ is the primary concern. The time it takes to regain this energy state is how energy plays an important role in the survivability aspect of today's engagements. The slower the aircraft remains the more vulnerable it is to enemy ground and air attack. For example, if the pilot enters an engagement at 400 knots calibrated airspeed (KCAS) and can turn 180 degrees 5 seconds faster than his adversary, this gives the pilot the capability to point at his opponent first and most likely employ the first weapon. Where energy comes into play is the ability to regain that initial state that the pilot had going into the engagement (i.e. 400 KCAS and the same altitude). If this takes him 5 seconds, most pilots would gladly trade this energy for the ability to employ a weapon (assuming a sterile (no threat) environment). But if regaining this energy

¹ *An aircraft's vulnerable cone is usually referred to as the portion of the aircraft that is most vulnerable to the type weapon being employed. In the case of an infrared missile, the area would consist of approximately a 45° cone behind the tail of the aircraft, while a radar missile could consist of the entire front aspect of the aircraft or more.*

takes the pilot 20 seconds, then most pilots would choose not to engage. The reason for this is that even though the pilot may think he knows the position of other threats, in combat the unexpected is what can get you killed. There are basically three significant maneuvers that the pilot uses to defeat his adversary. These are shown in Figure 1. The first is the minimum time turn. This maneuver is used in both offensive and defensive situations to either put the aircraft's nose on the adversary or rotate the aircraft's vulnerable cone so the adversary cannot employ his ordinance. The second is the acceleration maneuver. This maneuver can be used to run from an adversary, gain calibrated airspeed to perform the maximum turn, or catch an adversary that is trying to escape. The last maneuver is the loaded roll. Applications for this range from trying to overshoot an adversary approaching from the rear to remaining unpredictable while pointing the nose in a desired direction. All these maneuvers and combinations of maneuvers are extremely important in today's combat arena. Metrics to measure an aircraft's capability to perform these maneuvers are just as important as the maneuvers themselves. This will give the pilot the ability to compare his aircraft with an adversary aircraft and determine where he has the advantage or disadvantage.

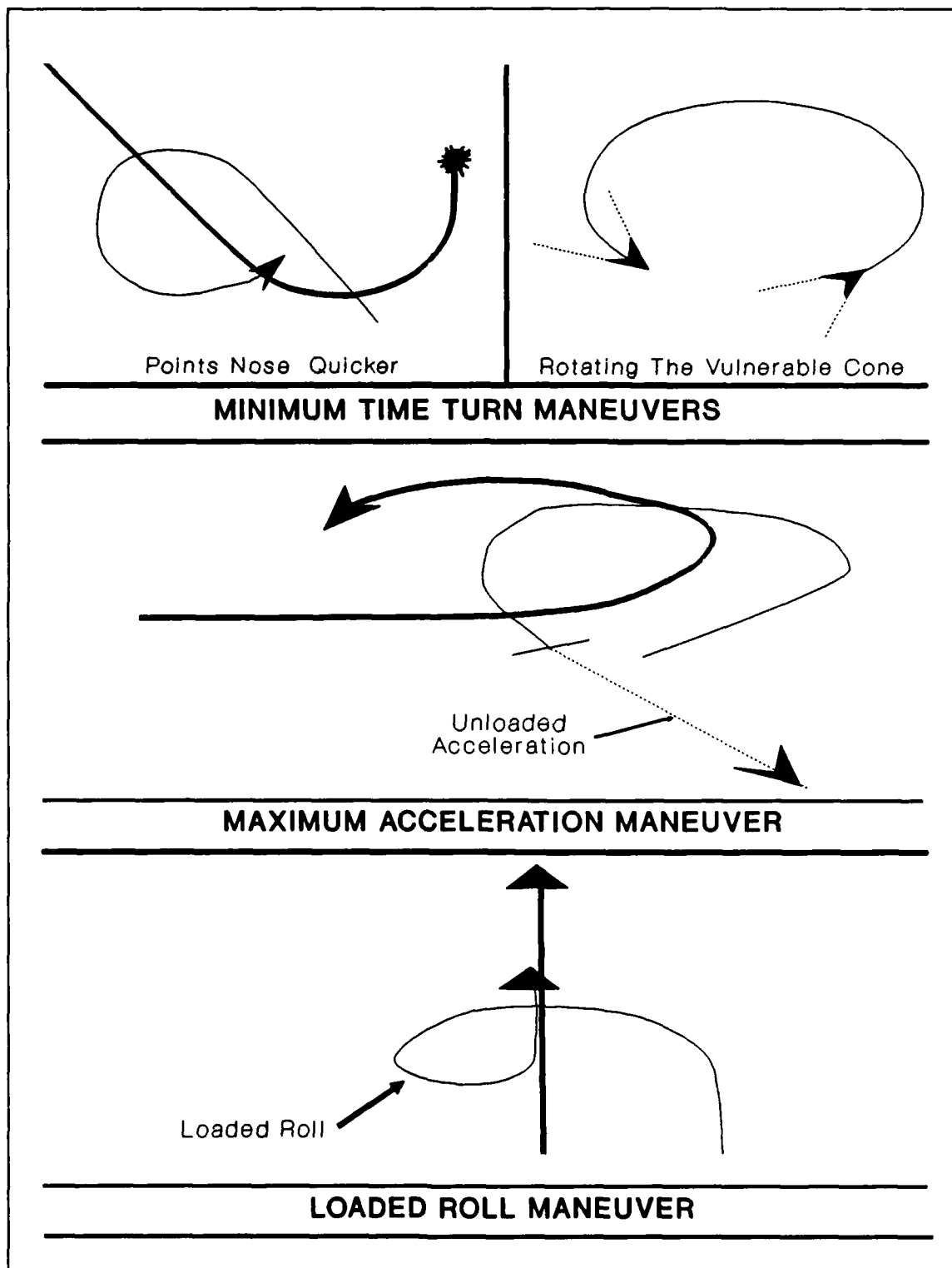


Figure 1. Typical Air-to-Air Combat Maneuvers

In the following section the basics of these new metrics will be developed to assess or compare the capability of an aircraft in this area.

III. Metric Development

Several members of U.S. Air Force, government and aerospace industry have been working on the development of metrics to measure agility. Thus far several different approaches have been taken with varying degrees of merit. To the engineer, many of the metric styles already developed can be very useful in the design aspects of agility, but from the pilots point of view, the major problem with most of the metrics is their complexity and lack of transferable physical meaning. While most of the metrics developed thus far can be used to compare aircraft in various ways, the difficulty of how a pilot can use this information to gain an advantage over his adversary is the major problem in applying these metrics to operations. The need for metrics that are easy to assess and that compare aircraft, using physical relationships a pilot can understand, is paramount. To decide on the metric style that takes these factors into account, there must be a clear understanding of the work done and the methods of data presentation. To do this, the desired aircraft agility must first be discussed.

The pilot wants the ability to point his nose at the adversary and launch a weapon before the adversary points his nose at him. The decision to perform a particular maneuver will be based on certain tradeoffs and the combat environment. Several factors will drive the decision to engage an adversary. The first and foremost will be

the ability to survive the engagement. If the pilot feels he can employ his weapon first and have enough airspeed to not be a "sitting duck" for another enemy aircraft the decision to engage will probably be made. On the other hand, if he feels that he will lose too much airspeed performing the maneuver and cannot get that airspeed back quick enough, a decision to pass the engagement will most likely be made. Two types of agility play a very important role in this type of decision making. These are pitch and axial agility.

III.1. Pitch Agility Metric

The ability to rotate the aircraft pitch axis quickly (whether about the lateral axis, a fixed inertial reference or a combination of both) will be called "pitch agility". This definition does not limit the plane of motion of the aircraft. Pitch maneuvers can be accomplished either vertically, horizontally or in any combination. The question is "how fast can I point my nose at the other aircraft and how much airspeed will I lose in doing so?" These specific types of maneuvers and presentation methods have been explored by several researchers. Some of the methods of presentation are discussed below.

III.1.a. Air Force Flight Test Center. First, the Air Force Flight Test Center (AFFTC) recognized the importance of the time portion of agility in their initial work [1]. The pitch agility plots in Figure 2 show the general ideas presented by the AFFTC and how they can be applied to this pointing ability. The graphs plot the

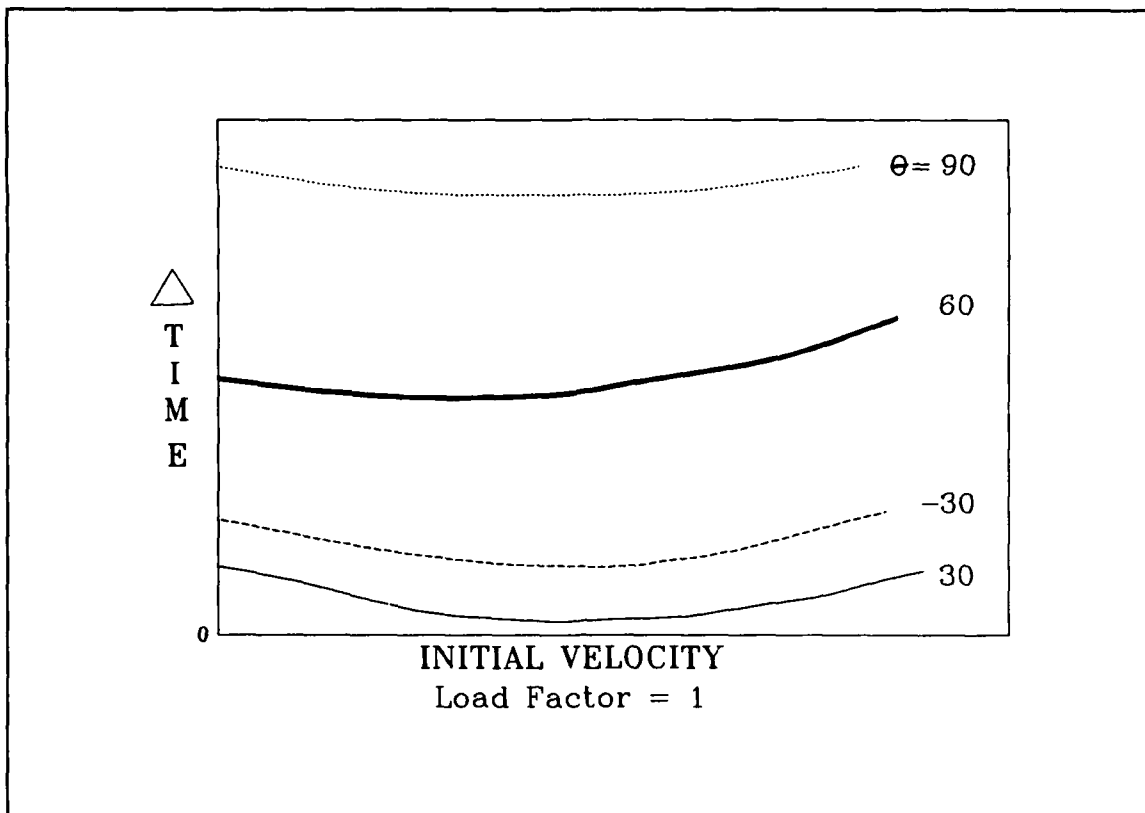


Figure 2. AFFTC Pitch Agility Metric Proposal

time required to complete the desired number of degrees of pitch change (depicted by the numbers to the right of each graph) against the initial velocity of the aircraft.

Each graph is done for a different starting load factor. While these plots are based on pure pitch agility with no angle of bank, this basic concept will also hold for level turning flight or with a set bank angle. Not only do the plots take into account the ability to move the nose to a desired position, but also the time to capture that desired nose position. Obviously, when using these for comparison purposes, each aircraft must be performing the same maneuver.

III.1.b. DT Parameter. Another idea was presented by Kalviste and Tamrat at Northrop [9:2-2]. The basic concept behind their idea is to maximize the turn rate and minimize the turn radius. To help explain this concept, three point and shoot trajectories are shown in Figure 3. These maneuvers can be performed in any plane of motion but must be compared using the same plane of motion. The points along the trajectories where the fuselage reference lines (FRL) have been rotated 180 degrees are shown by the times t_A , t_B , and t_C . The cross range distances at these

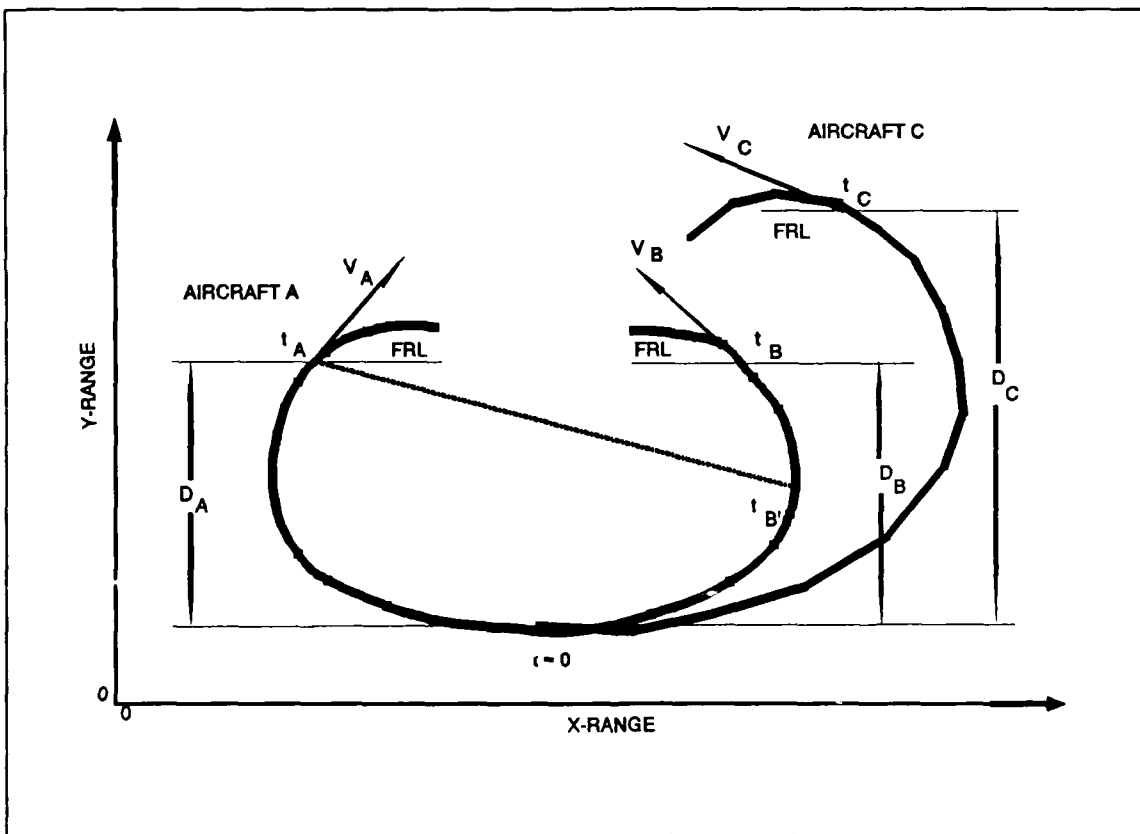


Figure 3. Point and Shoot Trajectories [9:2-2]

points are denoted by D_A , D_B , and D_C respectively. If two aircraft perform identically ($t_A = t_B$ and $D_A = D_B$) then the pointing solution occurs at the same time. If Aircraft C has a larger turn radius than Aircraft A but the times are equivalent, then Aircraft A will have a pointing solution before Aircraft C. Thus, the smaller the cross range distance the greater the pointing advantage. Now, approaching this from a time standpoint, when two aircraft turn 180 degrees with the same cross range distance but the times to reach that point are different, the aircraft that turns 180 degrees in the shorter time frame will have the pointing advantage. This is also shown in Figure 3 where $t_A = t_B'$. From these concepts the DT parameter is developed. Since turn rate is maximized, then time to turn is minimized. Turn radius is also minimized, therefore by multiplying these two parameters together (Distance X Time) a minimization parameter can be developed called the DT parameter. A graphical depiction of this is shown in Figure 4. The smaller this parameter the better the pitch agility of the aircraft.

Although this parameter can be of great use to the engineer or analyst trying to compare a specific parameter, to the pilot, this parameter does not mean much unless accompanied by supplemental data to extract some physical meaning. Both of the values that make up this parameter are very important in the agility picture, but the distance portion of this can be related directly to two other variables, one being the load limit of the aircraft and the second the angle of attack limit. As pilot capabilities and technology increases these load capabilities will increase, but for future fighters, the limit will not be the airframe, it will be the pilot. As aircraft are able to maintain

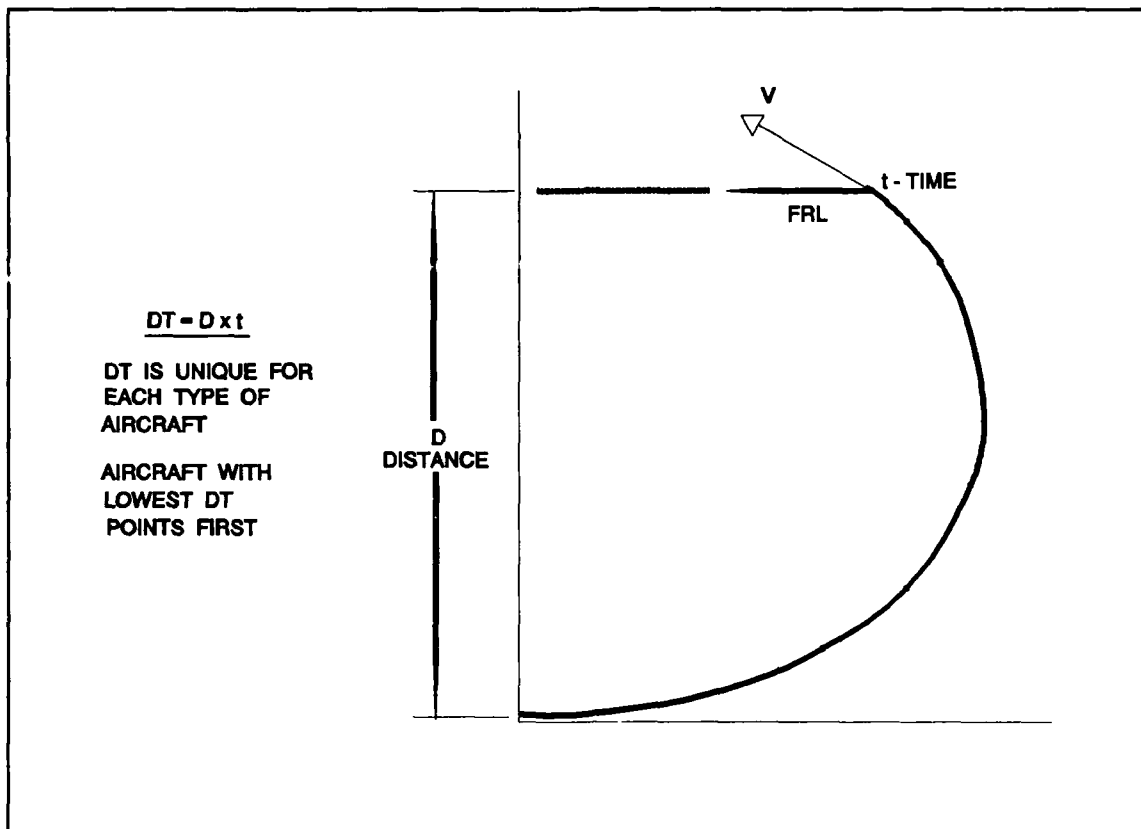


Figure 4. Definition of Point and Shoot Parameter (DT) [9:2-2]

higher angles of attack, the distance and time to point will both decrease. Therefore, the combination of these two variables will be directly related to angle of attack.

III.1.c. Dynamic Speed Turn Diagrams. One key factor in the decision to engage that has been omitted from the previous work is the amount of airspeed the aircraft will lose while performing this pitching maneuver. In McAtee's work at General Dynamics [12:65] the concept of the dynamic speed turn that accounts for this loss of calibrated airspeed was introduced. This is extremely important to the pilot in a fluid combat environment with multiple adversary aircraft. The dynamic

speed turn diagram was created by cross plotting the limit lines of the conventional energy maneuverability plots. These plots allow the reader to see the time dependency of performing maximum turns and straight line accelerations. To construct these plots, the acceleration must be computed for each point along the horizontal axis of the P_s chart; then two metrics can be drawn to show the maximum turn and acceleration potential. This concept is shown in Figure 5. The maximum

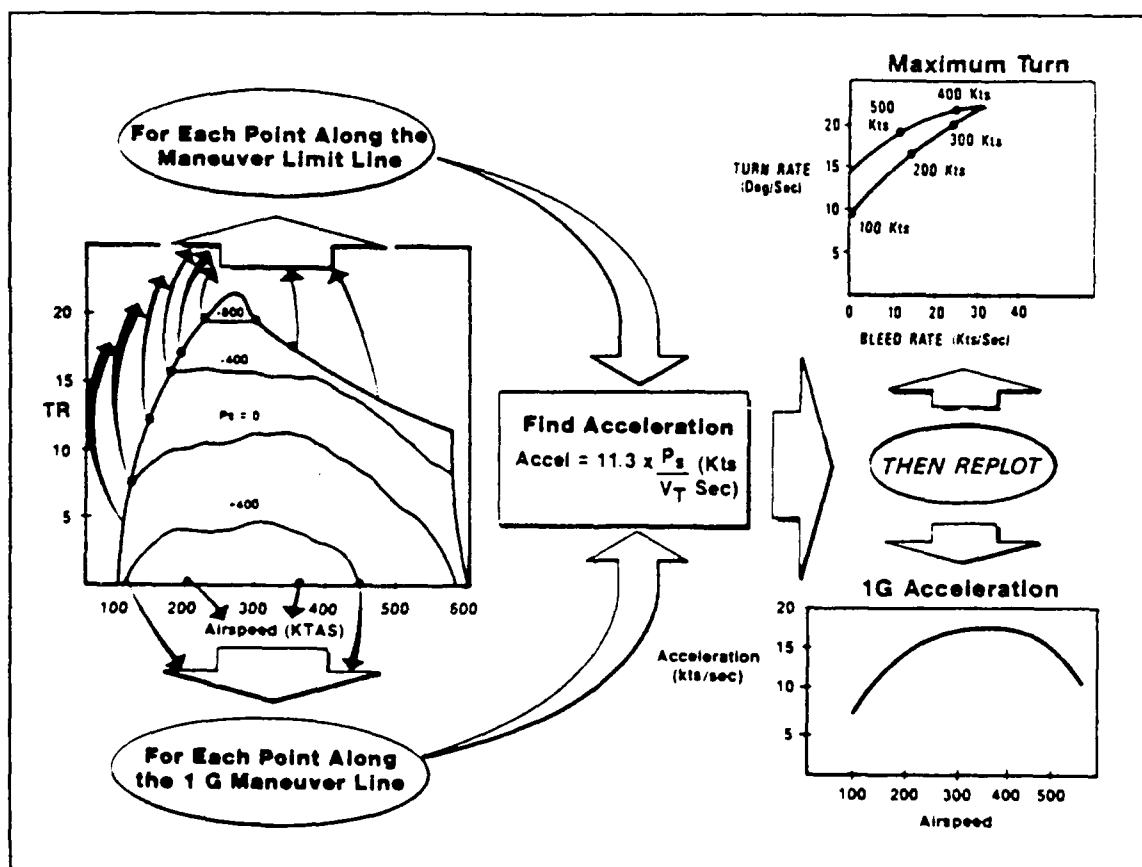


Figure 5. Dynamic Speed Turn Concept [12:65]

turn metric plots turn rate (TR) versus bleed rate with airspeeds referenced along the lines. The other plot is a 1 g acceleration line plotted across the airspeed spectrum. An example of this concept is shown in Figure 6. If this aircraft begins a maximum maneuver at 500 KCAS, the average deceleration over a period of 10 seconds can be period should be about 200 KCAS. Also from the maximum turn plot a rough estimate of the average turn rate can be made. This would appear to be about 18 degrees/sec. Therefore the aircraft would complete about 180 degrees of turn in this period of time and the velocity at the end of this time will be about 300 KCAS. This same type of analysis can be made using the acceleration potential diagram. If the aircraft starts at 200 KCAS and uses a maximum acceleration for 30 seconds, the average acceleration for this aircraft from the chart will be about 10 KCAS/sec. graphically estimated to be about 20 KCAS/sec. So, the total airspeed lost for this Therefore the aircraft will gain approximately 300 KCAS. These charts, if computerized, can be used to fine tune aircraft designs by extracting exact data and determining the proper balance between maneuverability and acceleration potential. Although these charts contain the data a fighter pilot desires, the problem with using these charts operationally is that it requires the pilot to mentally extract and calculate the important parameters he will use in a combat environment.

III.1.d. New Metric Development. Pulling the important parameters from the sections above, a metric can be developed that takes these important parameters and presents them clearly and simply to the pilot. The idea is to combine the pitch

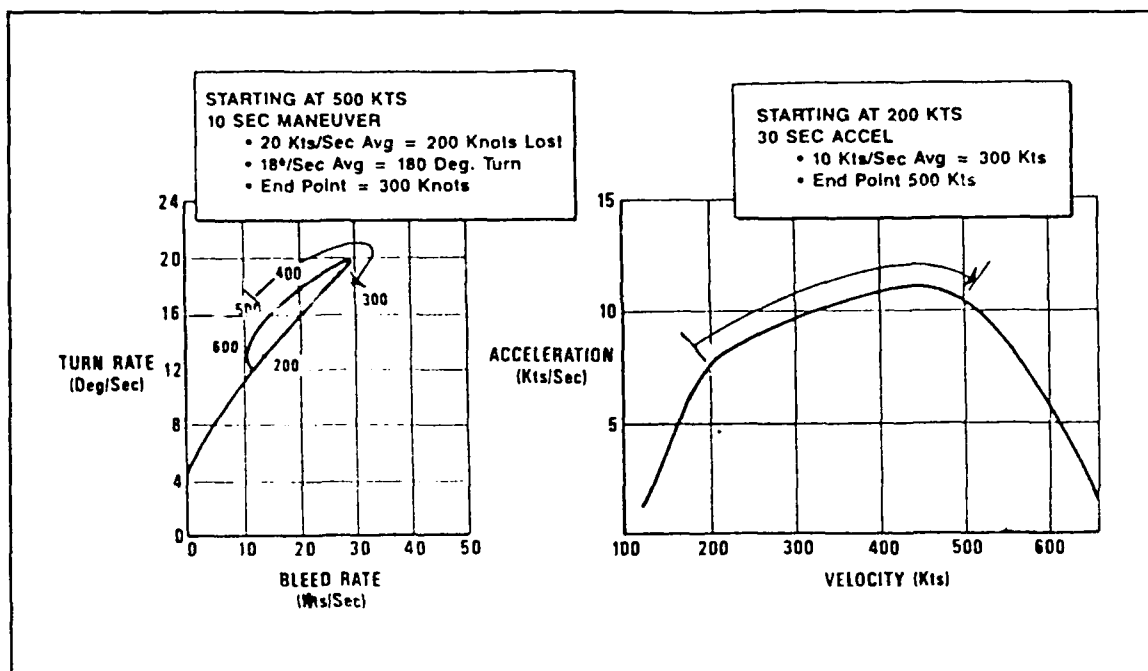


Figure 6. Dynamic Speed Turn Example [12:66]

capability of the aircraft with its susceptibility to bleed calibrated airspeed. Why calibrated airspeed rather than Mach number? To the fighter pilot, Mach number means very little. The reason is that the pitch rate of the aircraft and the ability to increase the aircraft's g loading is tied directly to calibrated airspeed. In today's conventional fighters, which are limited to 30 to 40 degrees angle of attack, calibrated airspeed control is the only way to point the nose without extreme excursions in angle of attack and increased departure susceptibility.

An example of a metric that could be used to evaluate these two factors is shown in Figure 7. The data of the turning capability of the aircraft is plotted as degrees turned versus time to turn while the ability of the aircraft to keep airspeed is plotted

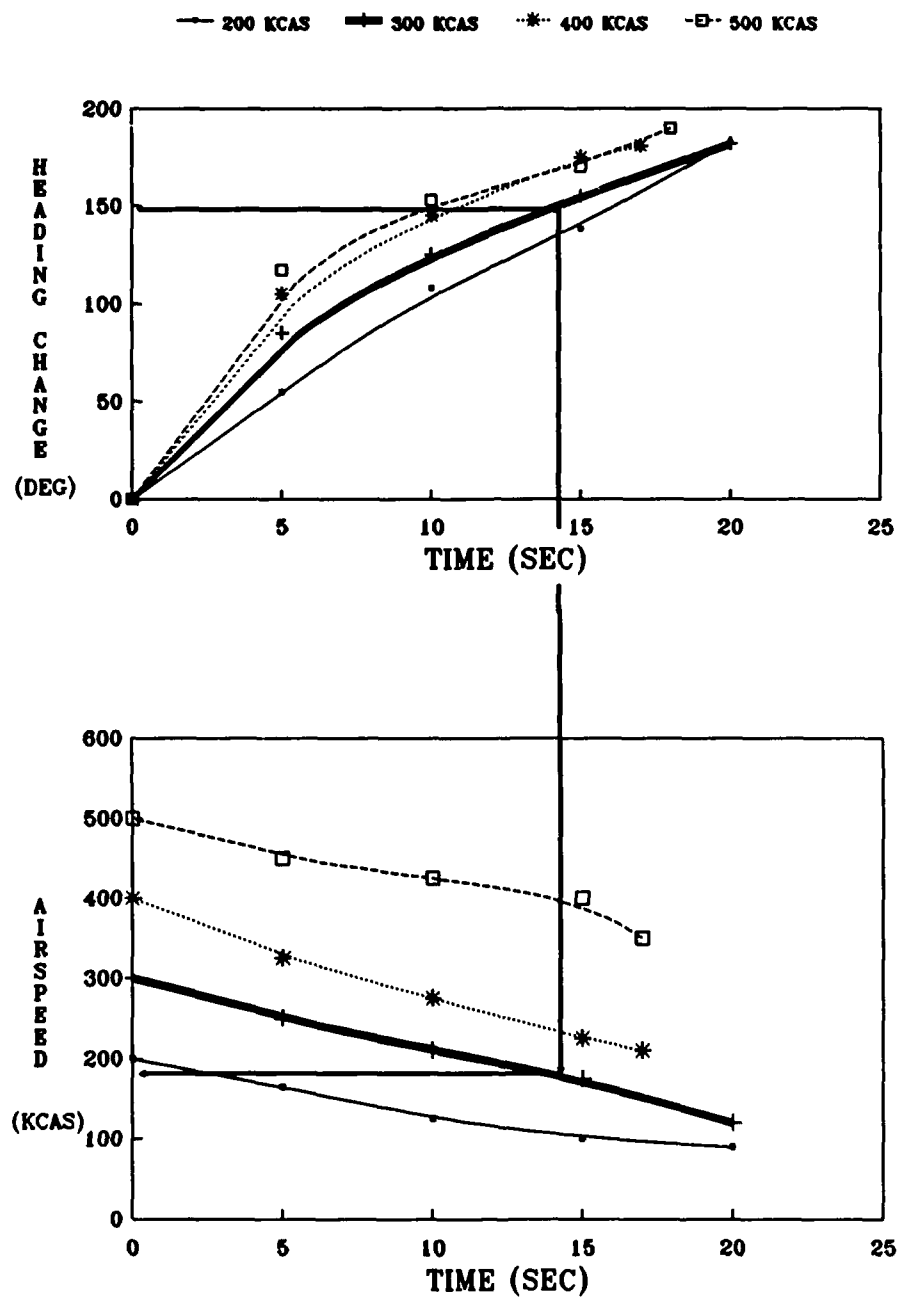


Figure 7. Proposed New Pitch Agility Metric

below this chart as calibrated airspeed versus time. The way this metric would be most commonly used is by determining the desired heading change (150°) and initial starting airspeed (300 KCAS) and move from left to right to the intersection of these two values. When this is found, drop vertically down to the time line and read the time to turn (14 seconds). To determine the final airspeed after this turn, continue vertically down to the line that coincides with the initial airspeed for the maneuver and then move horizontally to the left and read the final airspeed following this turn (180 KCAS).

Comparisons between aircraft can be made specifically as shown above or generally by looking at the shape of the lines. The larger the average slope of the lines on the upper graph the faster the aircraft will be able to point. The larger the average slope of the lower lines, the faster airspeed is lost in performing the turn. By reviewing this combination, not only can a pilot tell how fast an adversary can get his nose pointed, but also what kind of calibrated airspeed he will have once he does. A smart pilot would then compare these two parameters with the capability of his own aircraft and determine whether he will have an advantage from a neutral starting position in a given engagement scenario. Once again it is important to note that with this method of presentation, data can be extracted for any amount of heading change and not just 180 degrees.

III.2. Axial Agility Metric

The decision to engage, as discussed above, is also determined by the ability of the aircraft to decelerate and accelerate quickly. The desired performance, which may require quick deceleration, is the ability to point the nose quickly to obtain the optimum turn. The problem now is that the aircraft becomes very vulnerable to other adversary aircraft. If the pilot can decelerate quickly, launch a weapon, and accelerate quickly back to an airspeed that allows him to defensively react to another adversary, if need be, he will most likely decide to engage the adversary. By increasing the pilots chances to survive an engagement, the ability to maintain air superiority will be enhanced. Another application of this type of agility is in the separation phase of the engagement.

When a pilot decides to separate from an engagement it can be due to one of several reasons; he may be out of ammunition, out of fuel or be outclassed by the opposing pilot. Whatever the reason, once the decision is made and the action begun the pilot better have the ability to accelerate to high speed very quickly and get out of his adversary's weapons launch zone if he expects to survive. Once again this ability to out-accelerate the opposing aircraft will weigh into the pilots decision to engage in the first place. But more importantly, it gives him an escape option he may need in a sticky situation.

III.2.a. Air Force Flight Test Center. Work done at the Air Force Flight Test Center takes into account the direct acquisition of this data, but the method of

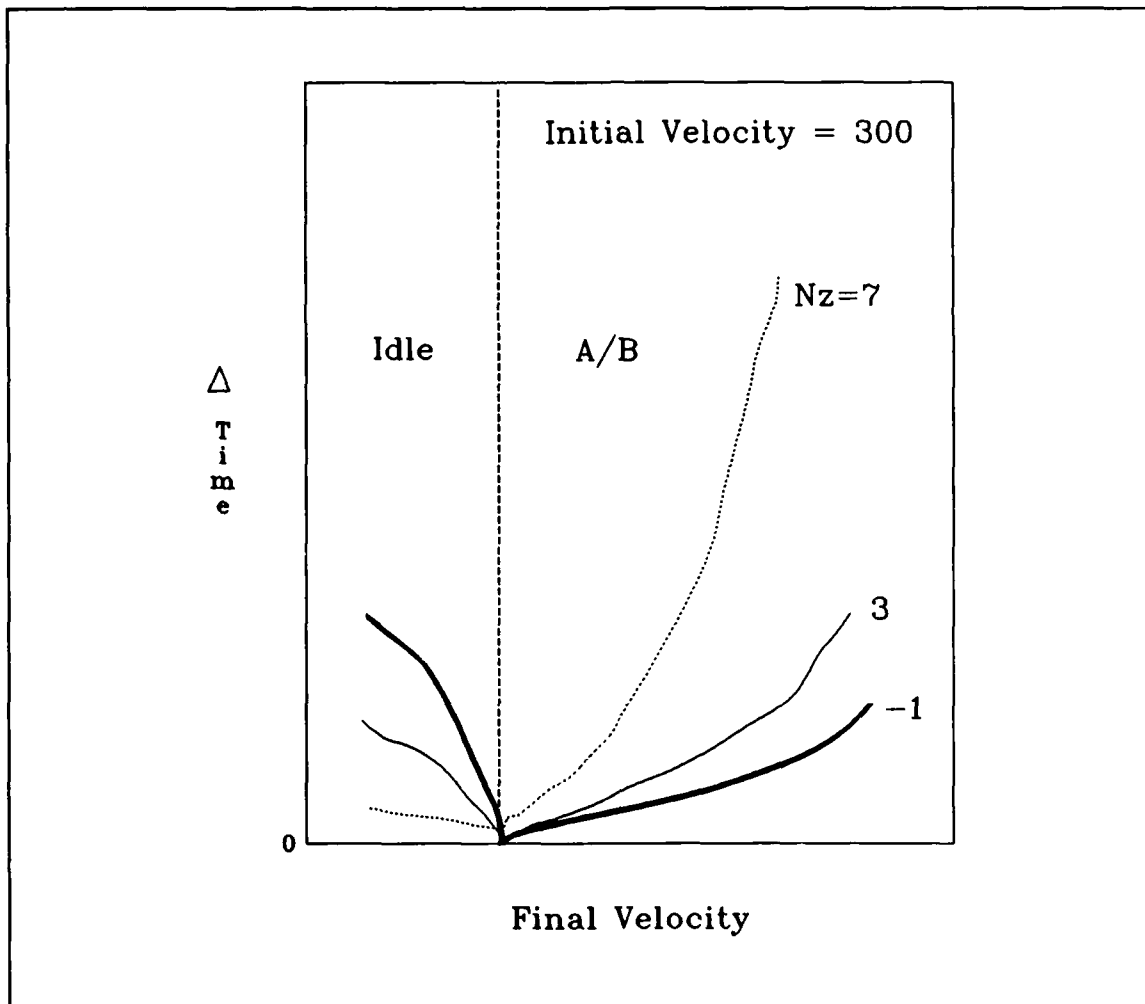


Figure 8. Time to Final Airspeed versus Final Airspeed

presentation requires several charts to see a full range of values [1]. Two methods of presenting this data are shown in Figures 8 and 9. The first method plots time to accelerate to a specific final airspeed versus initial airspeed for different g loadings. Several charts must be made to account for various final airspeeds. The second type of diagram is one plotting time to accelerate from a specific initial airspeed versus final airspeed for several different load factors. Once again several of these charts

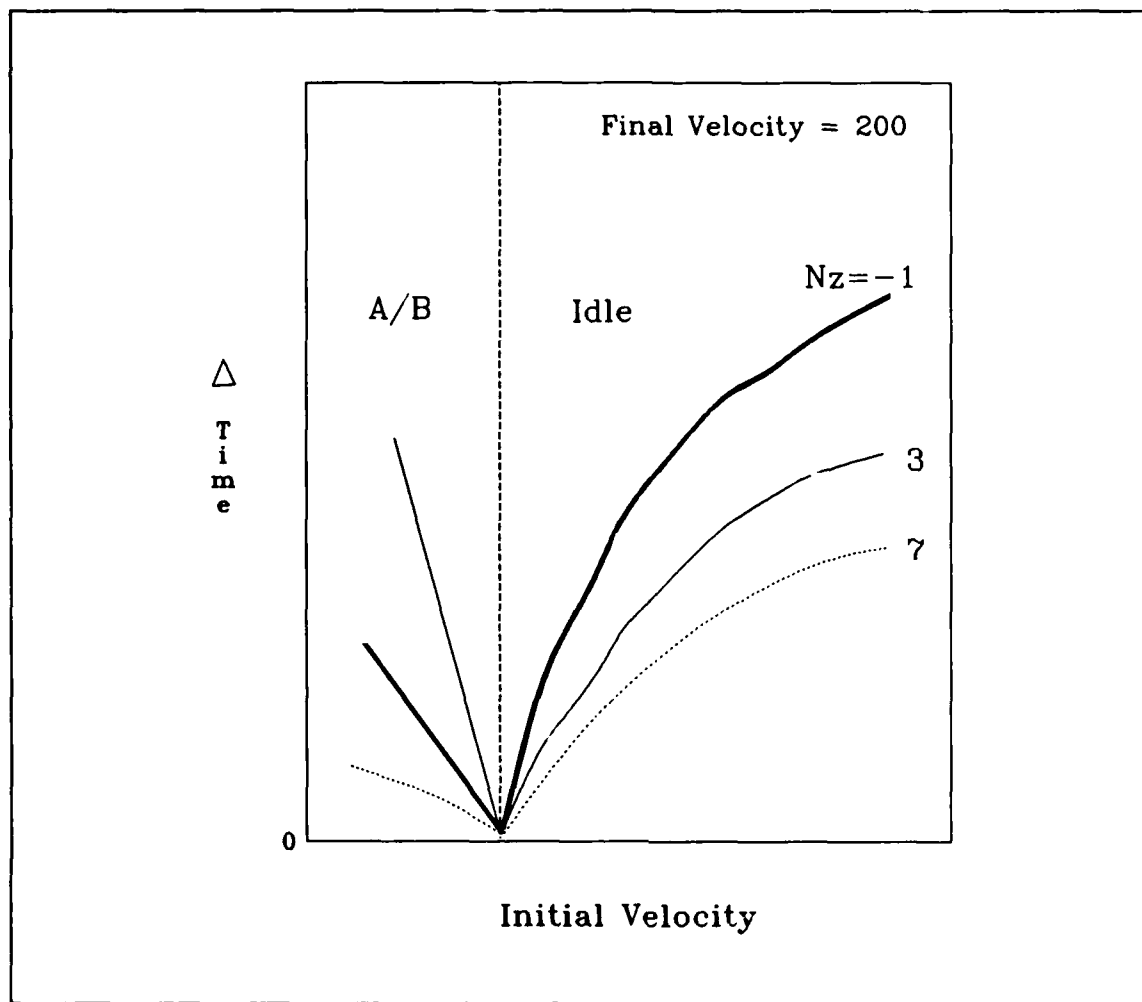


Figure 9. Time to Final Airspeed versus Initial Airspeed

must be made to account for different initial airspeeds. The reason these methods require several charts is that acceleration and deceleration data is calculated for several load factors. While this might be very important to the designer in fine tuning a design, this data is basically irrelevant to the pilot and hampers his ability to extract the data needed to determine the aircraft's maximum acceleration capability.

III.2.b. Dynamic Speed Turn. From the ideas presented above, it is easy to see that the important parameters for a metric to measure the axial agility of an aircraft are airspeed and time. From the discussion in the last section, McAtee's work with the dynamic speed turn concept makes use of the aircraft's ability to accelerate. This was shown in Figure 5. In his work, he points out that the current energy-maneuverability diagrams do not take into account how fast airspeed can be attained or how fast it can be lost. The P_z diagram basically shows what happens during steady state maneuvers and does not show acceleration trends over a period of time.

III.2.c. New Metric Development. As discussed earlier, in today's air combat engagements the pilot does not try to continue to turn while gaining airspeed. To accelerate the aircraft, the pilot will unload to a g loading that will give the best acceleration capability and use any available device (i.e. thrust vectoring, jet assist, drag reduction, etc.) on the aircraft to gain an acceleration advantage. Thus, when developing a metric to compare the acceleration capabilities of fighter aircraft, it should be done at the aircraft's best acceleration flight condition. Figure 10 shows a candidate metric to measure this agility. In this figure the solid lines represent the ability to accelerate and are plotted with airspeed on the vertical axis and time on the horizontal axis. Each line begins at a different starting airspeed and ends at a desired ending airspeed. The data presented in this metric should be taken at the aircraft's best acceleration loading and should compare aircraft at their best acceleration flight

condition. The deceleration capability of the aircraft can be represented during 1g flight using all available drag devices (i.e. speed brakes, thrust attenuators, thrust reversing, etc.) to gain a deceleration advantage. Although the aircraft will obviously decelerate quicker if the g loading is increased, the primary purpose of this metric is to determine how the design of the drag devices, engine deceleration and basic airframe characteristics effect the ability to decelerate without load. The deceleration capability is represented by the dashed lines and is plotted exactly like the acceleration data.

III.3. Rolling Agility Metric

The final metric that will be developed is one for the loaded roll. This maneuver, as discussed before, has several combat applications that are very important. One of the most important applications is the ability to roll around the velocity vector while using the maximum g loading and best axial deceleration capability to cause the adversary to overshoot from an offensive position. The quicker the aircraft's rolling capability and the ability to stop the nose at a desired position are of the utmost importance in defeating an adversary using this type of maneuver. Although the maneuver described above is used in conjunction with a deceleration maneuver, it is very important to gain the knowledge of how the aircraft rolls at several different airspeeds and g loadings to be able to predict its capability at different flight conditions. Several companies have submitted ideas for the measurement of this type of maneuver.

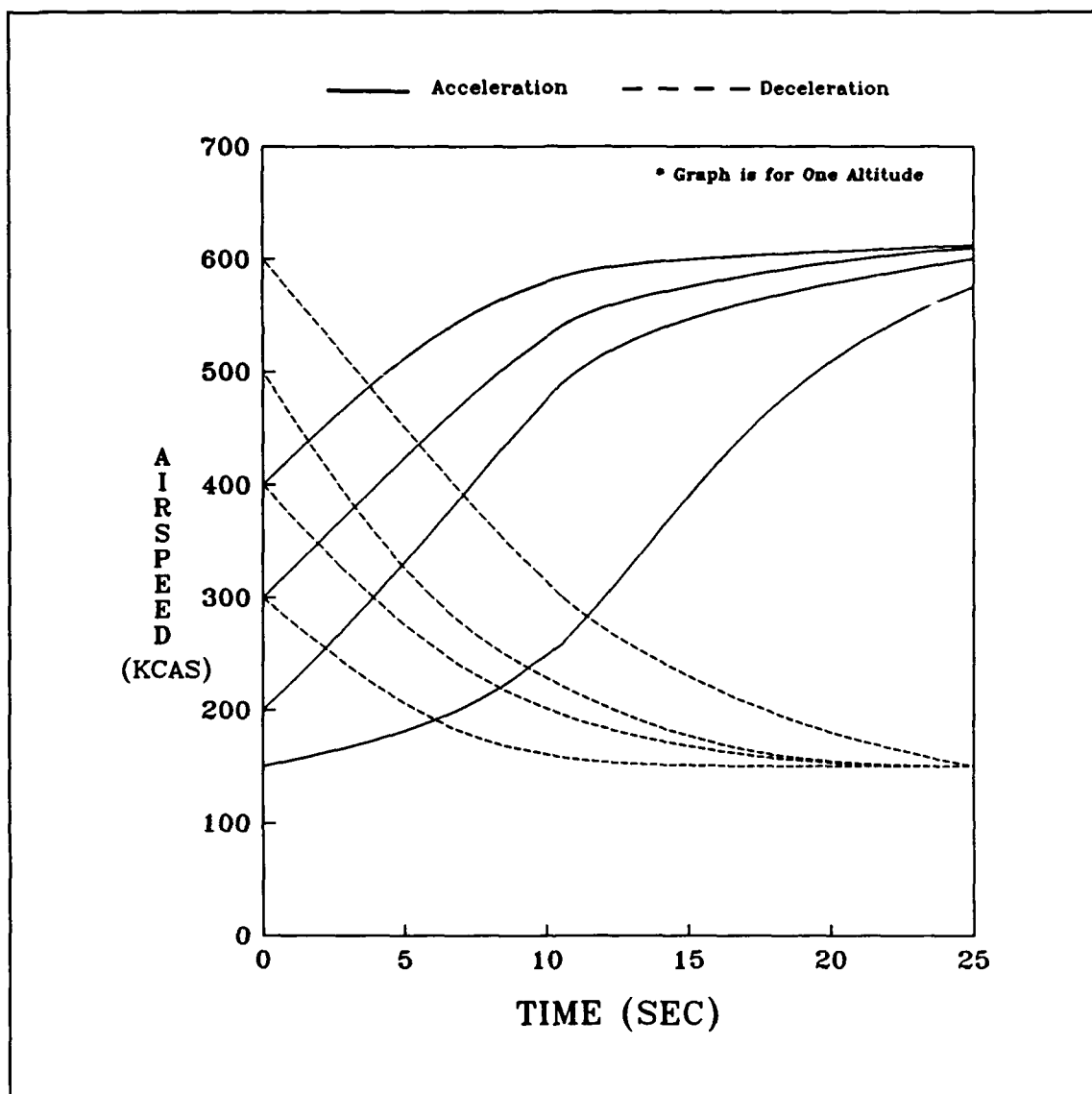


Figure 10. Proposed New Axial Agility Metric

III.3.a. Air Force Flight Test Center. The Air Force Flight Test Center presented the metrics shown in Figures 11 and 12. The first of these, plot the time to bank versus initial airspeed for several different load factors. This method also requires several charts to be made to account for various degrees of bank angle

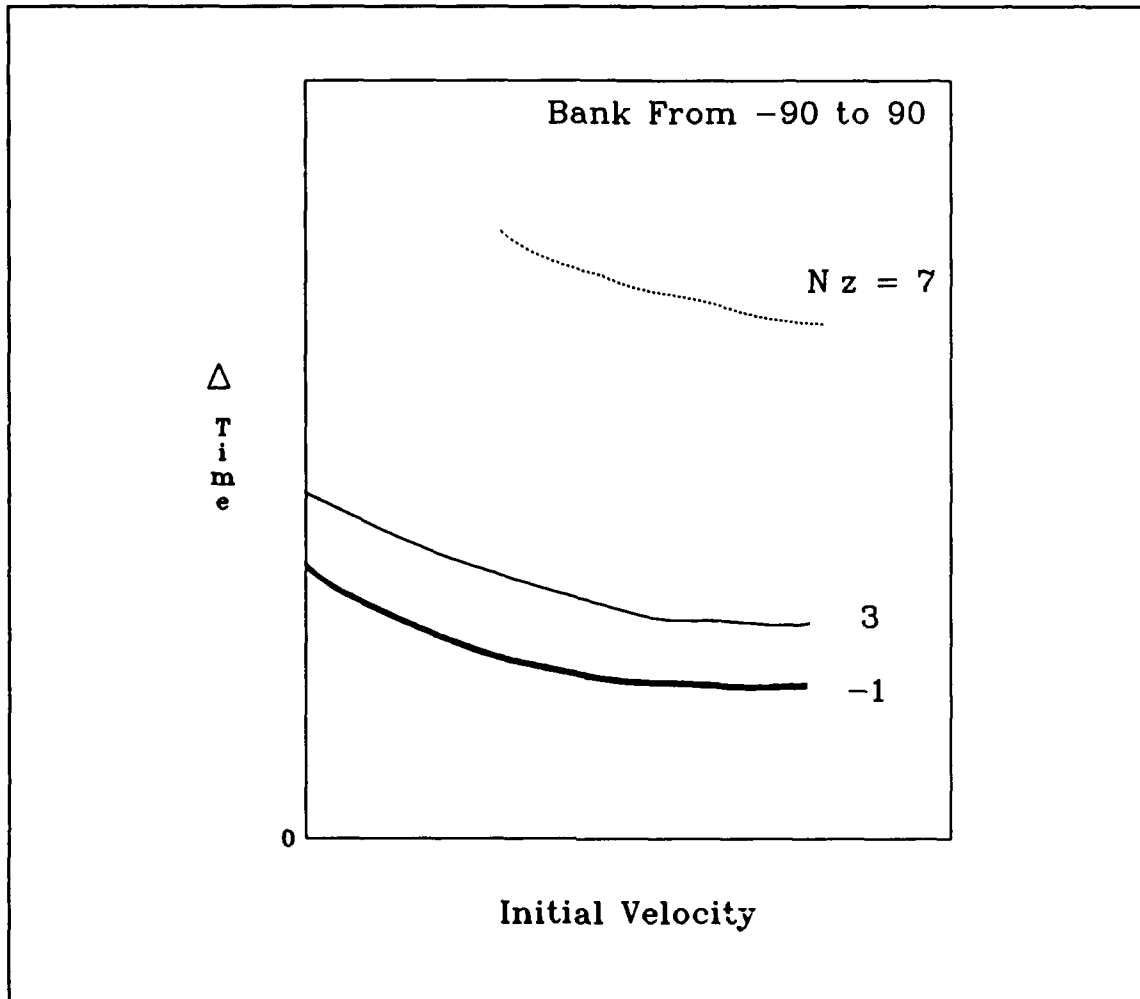


Figure 11. Time to Bank versus Airspeed for Different Load Factors

change. The second technique used by the AFFTC is plotting time to bank versus the change in bank angle for a specific airspeed at several different load factors. Once again a number of different graphs must be made for various starting airspeeds.

III.3.b. Eidetics International. Another technique used to plot the same data was developed by Skow of Eidetics International [14:4-38]. This is shown in Figure

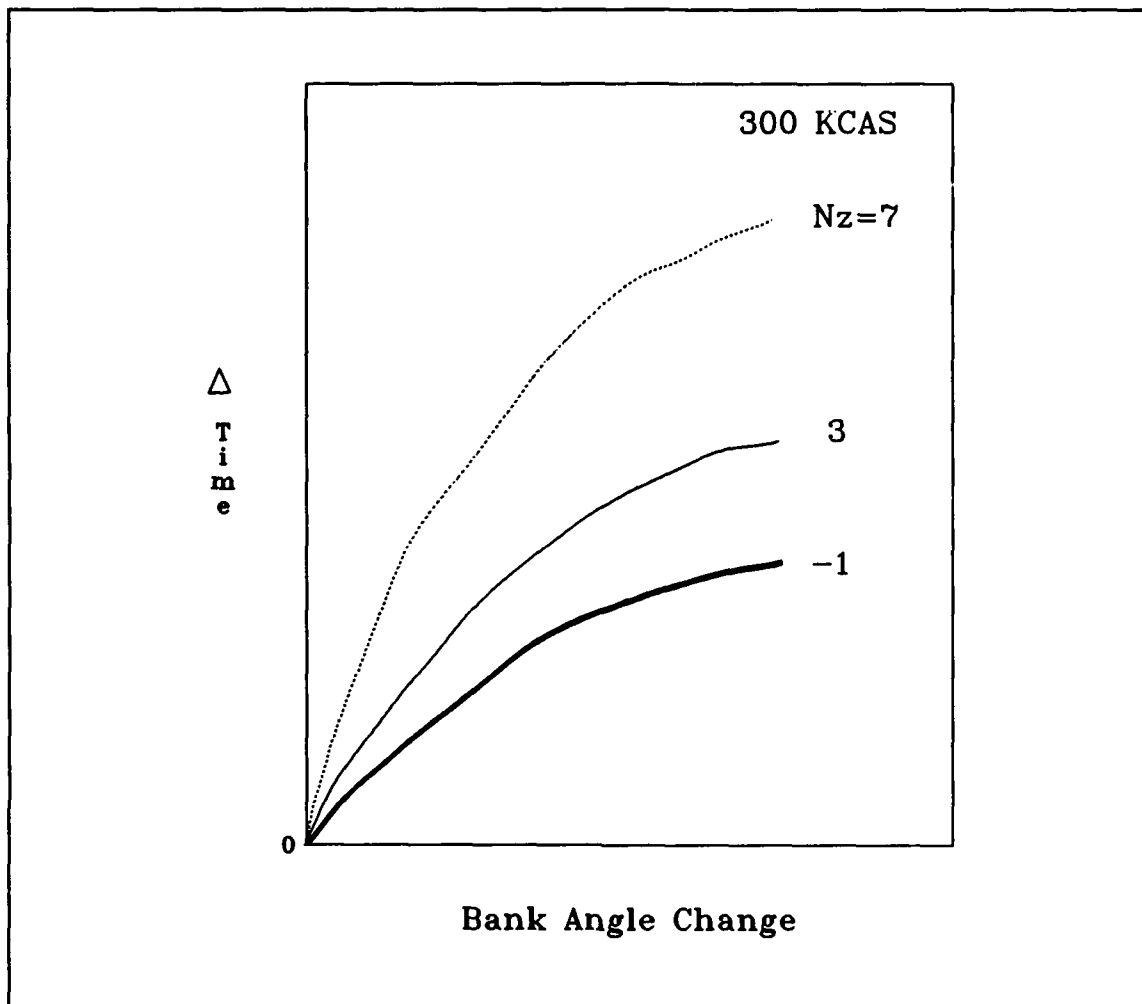


Figure 12. Time to Bank versus Bank Angle for Different Load Factors

13. This graph plots the time to roll the aircraft versus load factor for several different airspeeds. It also requires that a specific bank angle change be made. The ending angle of attack is also shown on this metric. Once again several of these charts must be made to account for different changes in bank angle.

III.3.c. New Metric Development. Both of the above methods are very effective in presenting this type of data, but are limited by the maneuver chosen (i.e. time to

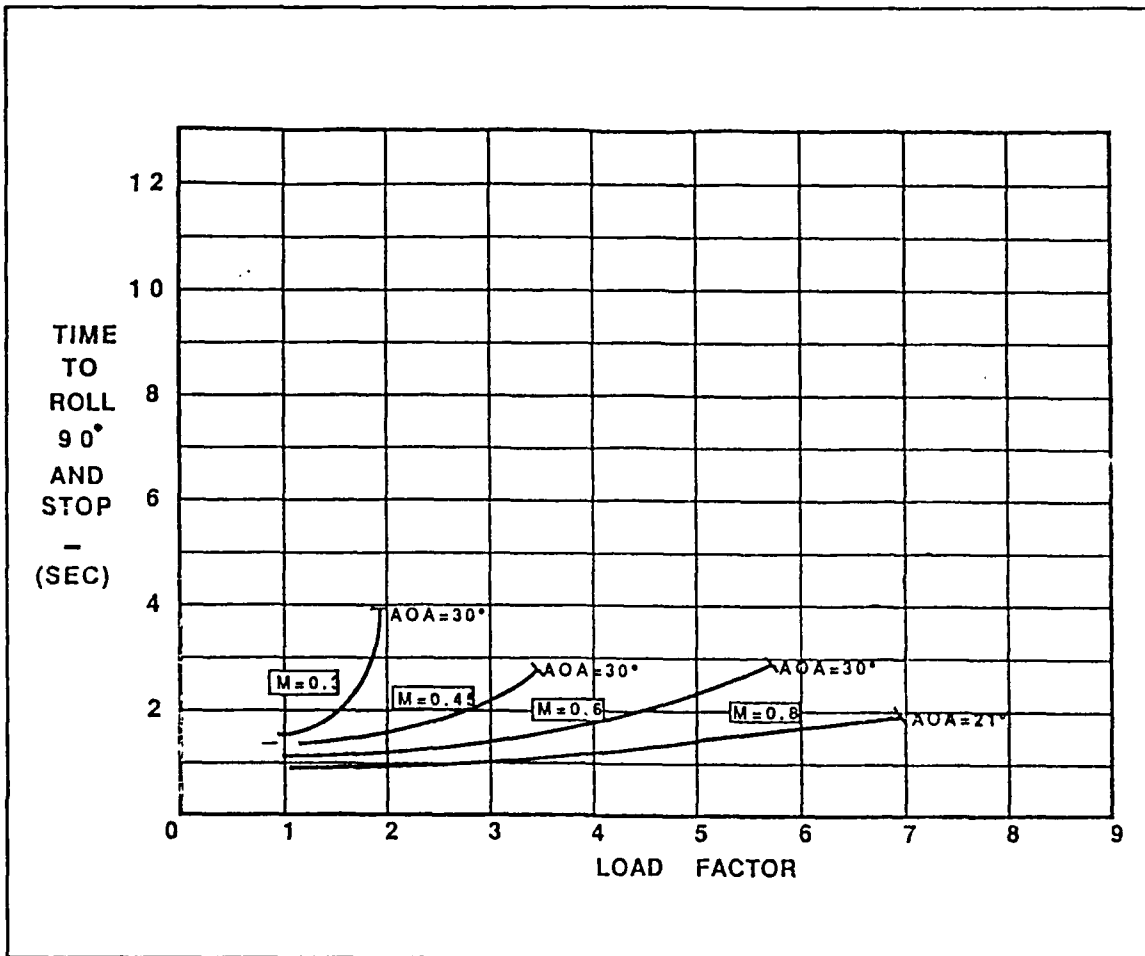


Figure 13. Eidetics Roll Agility Metric Proposal [14:4-38]

roll 90 degrees and stop or bank from 90 degrees to 90 degrees). To be able to extract data from any maneuver that is desired, the data must be plotted in degrees versus time. Due to the large variety of conditions involved at one specific altitude, this metric will require more than one chart. The easiest method to compare how the aircraft reacts at a specific starting g load is to plot each chart at that starting g load and specific altitude. Once this is accomplished, the data is plotted using different starting airspeeds. An example is shown in Figure 14. The 5g plot shows the

consequences of adverse coupling effects that might occur during testing. The 200 KCAS line shows early termination due to this roll coupling effect. The 150 KCAS line is left off entirely showing that the aircraft has no capability to reach 5gs at the 150 KCAS flight condition. This will be discussed further in the development of test maneuvers section. The transient portion at the end of the maneuver is shown above the 180 degree point and can be transferred to any portion of the curve once a steady roll rate has been obtained (i.e. once the slope of the curve straightens).

DEGREES ROLLED

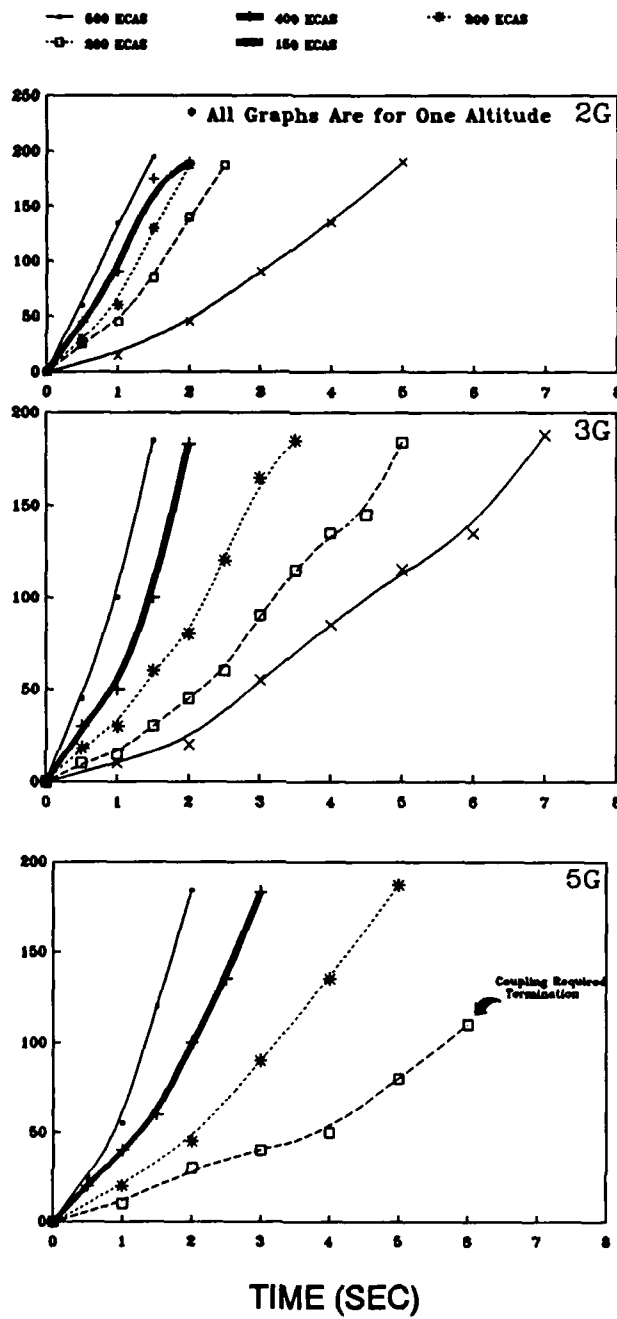


Figure 14. Proposed New Roll Agility Metric

IV. Flight Maneuver Development

Many different flight test techniques (FTT's) have been developed in an attempt to measure the agility of fighter aircraft. Most of the techniques, thus far, have come from the Air Force Flight Test Center. The primary objective behind these maneuvers is to obtain useful agility data in the minimum amount of time. These maneuvers must also be repeatable so the data from different flight conditions or different aircraft can be compared. Several of the FTT's to this date require the pilot to use an extremely difficult crosscheck of the desired parameters causing the maneuvers to be basically unrepeatable. Other techniques are more easily performed, but due to different piloting technique they also become unrepeatable. The following sections will look at some of the methods that have been used in the past and, using some of the lessons learned, new FTT's will be introduced to obtain agility measurements.

IV.1. Minimum Time Turn FTT Development

Pitch agility is the property that most of the agility work thus far has concentrated on. Although methods are widely varied in acquiring the data for this type of agility, basically the parameters of interest are the same no matter how the data is taken. The ability to acquire the data efficiently and with repeatability has been the problem up to

this point. Many different techniques have been suggested to obtain this data with varying degrees of success. The distinction between pure pitching motion as the pilot knows it (i.e. aircraft wings are level with horizon) and turning motion (i.e. aircraft wings banked with respect to the horizon) is basically only the plane of motion that the aircraft is moving in. The aircraft will repeatably perform a pitch maneuver in either plane of motion. The problem with a maneuver that uses the wings level type approach is that gravity plays a significant role in the outcome of the maneuver. One test report that used the wings level method was USAFTPS-TR-87A-S04, T-38A/F-16B Agility Metrics Evaluation, "Agile Lightning". A complete description of the FTT used is located in Appendix B. Some of the problems the test team noted were difficulty in setting up the maneuver and the high airspeed bleed-off as the maneuver was completed. Similar problems were noted in the test report USAFTPS-TR-87A-S05, RF-4C/F-16B Agility Metrics Evaluation, "Agile Thunder". This FTT is also located in Appendix B.

The level turn approach also has its faults due to the increased workload and crosscheck required of the pilot. This method requires the pilot to compensate by using bank angle to correct for altitude loss. This type of maneuver can also cause the pilot to inadvertently release back stick pressure to compensate for altitude loss which would hamper repeatability. This level turn method was used in USAFTPS-TR-88B-SO.5, F-15B Agility, "Have Agile Eagle". Some of the best techniques seen thus far are found in the aforementioned Agile Eagle report, due to the number of different maneuvers performed. The level turn FTT can also be found in Appendix

B. A few modifications to these techniques are applied to the FTT in the next section. This new approach attempts to simplify the maneuver and enhance repeatability to obtain basically the same data.

IV.2. Minimum Time Turn Flight Test Technique

The FTT described below uses some of the same flight test techniques described in the F-15 work described in Appendix B. One of the major differences is that only one heading change is made therefore simplifying and reducing the amount of data generated. The information for other heading changes can be obtained if the data is presented in a format such as that described in the agility metric section of this research effort.

Flight Test Technique

This maneuver should be initiated from level flight at the desired altitude. The fixed target at a distance on the horizon will be the reference point used to terminate the maneuver. Once the target is acquired, point the aircraft at the target and set the heading set marker on the present aircraft heading. Turn 180 degrees away from the target. Once established on this initial heading, set the airspeed 50 KCAS below the desired target airspeed to allow time for afterburner initiation. To start the maneuver the pilot should select full afterburner and accelerate to the target airspeed. Approaching the target airspeed the pilot should initiate a right or left hand roll to 90 degrees of bank angle. At the target airspeed the pilot should use a pure longitudinal stick input to one of (or a combination of) the following four conditions:

- * Maximum aircraft g limit
- * Maximum aircraft AOA limit
- * Aircraft limiter (if equipped)
- * Best aircraft turning capability (if different from above)

Once 180 degrees of turn have been completed, the pilot should attempt to stop the tracking of the aircraft nose and stabilize on the target. Any oscillations that might develop should be countered. The completion of the 180 degree turn should be accomplished by use of outside visual cues. The ability to capture the target within an acceptable tolerance should be an indication of successful accomplishment of the maneuver. Set-up for this maneuver is starting airspeed and altitude dependent. At low airspeeds and high altitudes this maneuver should be set up higher above target altitude to allow the aircraft to descend through the desired altitude block while completing the maneuver. Ideally, the starting altitude deviation above should be equal to the ending deviation below. If uncontrollable wing rock is encountered during the maneuver then some of the longitudinal pressure on the stick should be released to reduce the AOA. The objective is not only to see how quickly the aircraft will turn 180 degrees with a pure longitudinal stick input but also to keep it controllable while doing so. This is all part of the agility measurements. Slight wing rock can be compensated for by using rudder and small aileron inputs.

Data

Start the timing at the initiation of g onset in 90 degrees of bank. Stop timing when aircraft's nose motion and heading are within the required capture tolerance. Timing should be concluded when the aircraft reaches the 180 degree heading change.

Tolerances

Starting airspeed for the maneuver must be within 5 KCAS of target airspeed and bank angle must be 90 ± 5 degrees. Altitude must be kept within 1000 feet of the desired altitude throughout the maneuver. The only exception to this would be if the amount of time required to complete the 180 degree turn will not allow the aircraft to remain in the desired altitude band. If this is the case, an expanded altitude band is permissible. Capture tolerance should remain within 105 milliradians (mils) signifying a 3 degree field-of-view weapon.

IV.3. Axial Agility FTT Development

The amount of work done in the past on axial agility is very limited. The only test results found to date were performed by the AFFTC in June of 1986 and are found in the report USAFTPS-TR-85B-S2, Agility Evaluation of the RF4-C and

T-38A Aircraft "Have Agile". The flight test technique used to obtain the data is shown in Appendix A. There are several problems identified with the technique used to obtain the data. The test team from the above report observed one major problem area. This was:

The flight test technique led to problems with both aircraft at higher Mach numbers. For the accelerations beginning at 0.7 and 0.8 Mach number, engine RPM had not decayed to idle prior to the acceleration. The time during the previous deceleration was insufficient to allow full engine spool down. This effect occurred in both aircraft, but was more prevalent in the T-38A. [15:19]

The spool down and spool up effect of a jet engine can have a considerable effect on the required data. If a portion of the data is taken with a totally spooled down engine while a portion is taken with the engine partially spooled up, the repeatability of the test results are questionable.

This brings to light one major question in axial agility testing. Should the airframe be tested separately from the powerplant or should they be looked at as a total system? The answer depends on the aspect of agility that is in question. For an airframe designer who is trying to maximize the agility of the airframe only, the powerplant anomalies should be disregarded. But, for the pilot and the threat analyst, the engine performance is a very important part of the total axial agility package. In the following work, total system agility will be the topic of concern.

Another problem that is related to the powerplant question presented above, is the actuation of drag devices. Obviously, these items are an integral part of the airframe

and should be considered during axial agility testing, but the use of these devices must be completely specified to insure repeatability among a wide range of pilots. Specific instructions defining exactly when to deploy and retract these devices must be included in the FTT.

Much of the axial agility data could be estimated by the use of thrust decks, drag polars, drag device effectiveness versus airspeed, engine spool up and spool down times, and drag device actuation time versus airspeed. Flight test of these separate items must be conducted to obtain the data required for the estimate. Whether this type of data gathering is more efficient than testing the axial agility using an FTT is yet to be seen. For older aircraft most of the data is already available. For new aircraft testing, an axial agility FTT may be able to provide not only the desired agility results but also some of the data required above to compute the results analytically. In any case, the analytical results must be confirmed using some type of FTT. A suggested FTT for this purpose is provided in the next section. Although this maneuver could be applied to supersonic flight as well as subsonic flight with a few minor adjustments, this technique will only address the subsonic portion.

IV.4. Axial Agility Flight Test Technique

To insure this maneuver is repeatable and performed in the same manner by all pilots both the acceleration and deceleration portions will be performed at a 1 g aircraft loading. Although this may not be the loading where the aircraft accelerates best, several present day aircraft have limitations on the amount of time they can

remain at 0 g. If all aircraft are tested at the 1 g condition, a valid comparison can be made and a more repeatable test profile can be obtained. The following is a description of the overall FTT. This maneuver is designed to account for limitations in throttle movement, engine spool up and spool down times and also for actuation time of acceleration and drag devices. These are very important parameters in the overall axial agility of an aircraft and must be accounted for. If flight time and fuel are available, each of these maneuvers should be performed at least three times to account for afterburner lighting variations and then averaged for the final result.

Flight Test Technique

To begin the maneuver, position the aircraft at target altitude and at 50 KCAS above the starting airspeed in level, unaccelerated, 1g flight. At this point, move the throttles to idle (do not employ any drag devices) and decelerate to starting airspeed. At the exact starting airspeed, move the throttles to maximum power and accelerate to the target airspeed using all available acceleration devices. For the deceleration portion of the flight test, start the maneuver in 1g level, unaccelerated flight 50 KCAS below the starting airspeed. Move the throttles to military power and accelerate to the starting airspeed. At the exact starting airspeed, move the throttles as quickly as allowed to idle, employ all available drag devices and decelerate to the target airspeed. Both the acceleration and deceleration maneuvers should be accomplished at several different starting airspeeds. The acceleration portion should be terminated prior to supersonic flight (about .94-.96 Mach). The deceleration portion should be terminated at a safe minimum airspeed for level flight (about 150 KCAS in most fighter aircraft).

Data

For the acceleration maneuver, start timing when the starting airspeed is reached but before the throttle is moved to maximum power and acceleration devices employed since any restrictions in throttle movement and time to employ acceleration devices should be included in the overall axial agility. Stop timing when reaching final airspeed. Timing for the deceleration maneuver should begin when the starting airspeed is reached but before the

throttle is moved to idle and drag devices deployed. Stop timing upon reaching final airspeed.

Tolerances

The airspeed at the beginning of the maneuver must be within 5 KCAS of starting airspeed, altitude must stay within 500 feet of the target altitude and g loading for the entire maneuver must be between .5g and 1.5g.

IV.5. Loaded Roll FTT Development

Almost all work done to this point on agility has addressed some aspect of rolling agility with very limited success. The maneuver that has been attempted the most is one that requires the pilot to maintain an elevated load factor while rolling the aircraft to the desired angle of bank. The first three FTTs for rolling agility in Appendix C use this technique. The problem this presents for the pilot trying to fly this type of maneuver is enormous. All the pilots concentration goes to maintaining the required g loading during the maneuver and the other parameters suffer tremendously. The repeatability of these maneuvers is very questionable. The best maneuver attempted thus far is one done in USAFTPS-TR-88B-SO.5, F-15B Agility, Have Agile Eagle also found in Appendix C. The FTT used a pure lateral control input and allowed coupling between the roll and pitch axis to take place. This coupling associated with the loaded rolling maneuver is, in almost all cases, an undesirable characteristic. In the FTT presented in the next section coupling is allowed to take place and, with an agility metric that takes this into account, some qualitative judgments on the aircraft being evaluated can be made.

IV.6. Loaded Roll Flight Test Technique

The FTT presented here uses several lessons learned by the test teams that have attempted these maneuvers. In order to simplify the maneuver and make a more expeditious entry into the maneuver, some of the starting conditions were changed along with the rollout techniques.

Flight Test Technique

To set up this maneuver, the aircraft should be at a specific altitude and airspeed. The test maneuver should be performed at several different g loadings starting with 1g and adding 2gs each time the maneuver is performed up to the maximum sustained g for that airspeed or the maximum rolling g limit of the aircraft, whichever is less. For the 1 g maneuver, when stabilized in level, unaccelerated flight, slowly roll the aircraft 90 degrees left or right and stabilize for one second. Then roll the aircraft through 180 degrees in the opposite direction using a pure lateral stick step input. Do not stop the roll until the 180 degree point is reached. Once the 180 degree point is reached, stop the aircraft roll rate as quickly as possible using lateral stick inputs. For the loaded roll portion, stabilize aircraft in a turn at the target g loading. Trim the aircraft so there is no longitudinal stick force and set power to hold airspeed and g loading. When stabilized, roll aircraft in the direction of the turn to 90 degrees of bank and stabilize for 1 second. Reverse the direction of the turn using a pure lateral stick input. Once again roll through 180 degrees and upon passing 180 degrees of roll stop the aircraft roll rate as quickly as possible using lateral stick inputs. Expect the aircraft to couple during the maneuver. If the aircraft exhibits extreme coupling with the lateral stick input that would require forward stick force to maintain control, this should be noted in the test report as a limit on the agility of the aircraft and the maneuver should be terminated.

Data

Start timing when turn is reversed and stop timing when passing 180 degrees. Call a hack when the aircraft reaches 180 degrees of roll.

Tolerances

Initial airspeed must be within 5 KCAS of target airspeed. Initial g must be within .5g of desired and is allowed to deviate as the maneuver progresses. Altitude must be kept within 1000 feet of desired throughout the maneuver. Initial bank angle must be within 90 ± 5 degrees.

V. Simulator Test Procedures and Equipment

The desired objectives for this test were:

1. Evaluate agility flight test techniques for flyability.
2. Evaluate agility flight test techniques for repeatability.
3. Evaluate the suitability of agility flight test techniques for new agility metrics.

V.1. Simulator Setup

The simulator used during testing was the LAMARS (Large Amplitude Multimode Aerospace Research Simulator). A complete description of this system is located in Appendix D. The LAMARS simulator was configured with a high fidelity F-15C/D cockpit. The center stick had an F-15E control head. The heads-up display (HUD) was the wide field of view LANTIRN (Low Altitude Night Time Infrared Navigation) style HUD. The pertinent data that the HUD displayed is:

Aircraft g loading
Aircraft angle-of-attack (AOA)
Airspeed
Altitude

The CRTs in the cockpit were set up to display an attitude indicator and a HSI (Heading System Indicator). A backup g indicator, airspeed indicator and altimeter

were located on the lower center console. The throttle quadrant was the standard F-15C/D throttles with standard switchology.

The outside visual cues that were present was an earth/sky type display with no specific visual landmarks on the ground display. When specific outside references were needed for maneuver performance, a fixed point was marked on the horizon.

Motion was not needed for this simulation, but an inflatable g-suit was used for the desired seat-of-the-pants feel.

V.2. Simulator Test Procedures

The flight test techniques used in this test plan were those developed in Chapter IV of this document. For each maneuver a build-up approach was used. Each maneuver was practiced several times at that specific flight test condition to characterize control inputs and obtain anticipated flight parameters. Specific test points flown are located in Table 1 through Table 3.

All maneuvers were flown at 20,000 feet mean sea level. The fuel level was reset to the starting condition before each maneuver to insure there was no undesired center of gravity shifting. The 450 KCAS test points for each maneuver was flown first to insure uniform data gathering techniques for each maneuver.

Two configurations of the F-15C/D were flown. The first was a completely clean F-15C. The gross weight of this configuration was 37,000 pounds. The second configuration was the same aircraft with an empty centerline tank and 4 AIM-7 missiles mounted on the fuselage (2 in front and 2 in back) with 4 AIM-9 missiles

Table 1. 180 Degree Turn Simulator Test Points

RUN NO.	AIRSPEED (KCAS)	LOAD FACTOR (Nz)	ANGLE OF ATTACK
1	450	MAX. AVAIL.	
2	300	MAX. AVAIL.	TO 30 UNITS
3	200		30 UNITS
*4	450	MAX. AVAIL.	
5	300	MAX. AVAIL.	TO 30 UNITS
6	200		30 UNITS

* Configuration Change: Gross weight increased 8,355 pounds

mounted on the inboard wing pylons. The gross weight of this configuration was 45,355 pounds.

Table 2. Axial Agility Simulator Test Points

RUN NO.	INITIAL AIRSPEED (KCAS)	FINAL AIRSPEED (KCAS)	LOAD FACTOR (Nz)	SPEED BRAKE (OUT/IN)	THROTTLES (MAX A/B /IDLE)
7	150	450	1	IN	MAX A/B
8	250				
9	350				
10	450	150		OUT	IDLE
11	350				
12	250				
*13	150	450		IN	MAX A/B
14	250				
15	350				
16	450	150		OUT	IDLE
17	350				
18	250				

* Configuration change: Gross weight increased 8,355 pounds

Table 3. Rolling Agility Simulator Test Points

RUN NO.	AIRSPEED (KCAS)	LOAD FACTOR (Nz)
19	250	1
20		3
21	350	1
22		3
23		5
24	450	1
25		3
26		5
*27	250	1
28		3
29	350	1
30		3
31		5
32	450	1
33		3
34		5

*Configuration Change: Gross weight increased 8,355 pounds

V.3. Instrumentation

The simulator was fully instrumented to record all significant flight parameters.

The essential data recorded for each maneuver is listed in Table 4.

Table 4. Simulator Instrumentation Parameters

PARAMETER	180 TURN	AXIAL	ROLL
LOAD FACTOR	X	X	X
STICK POS.-LATERAL	X		X
STICK POS.-LONGITUDINAL	X		X
SPEEDBRAKE IN/OUT	X	X	X
CALIBRATED AIRSPEED	X	X	X
PRESSURE ALTITUDE	X	X	X
MACH NUMBER		X	
ANGLE OF ATTACK	X		X
VERTICAL VELOCITY		X	
HEADING	X	X	X
PITCH ANGLE	X		X
ROLL ANGLE	X		X
FUEL QUANTITY	X	X	X

VI. Simulator Test Results and Analysis

The simulator flight test was flown by the author who was previously qualified in the F-16. Approximately three hours of flight time was needed to complete all the desired maneuvers and obtain enough data points to confirm or deny FTT usefulness and repeatability. The flight test techniques described in Chapter IV were flown.

VI.1. Pitch Agility Testing

Several problems were noted in completing this maneuver. The worst problem was controlling the nose slice tendency the aircraft generated during the turn. This problem was accentuated at the low speed points where the nose ended up as much as 60 degrees below the horizon. At this condition airspeed was building rapidly and pitch control was becoming very sensitive.

Another problem directly associated with this was the inability to remain within the desired altitude band. Several practices were made to judge the extra altitude needed above the test altitude so an equal amount of altitude above and below the test altitude was obtained. Again the slower speed test points had the worst results requiring up to a 5000 foot altitude band to complete the maneuver.

With the nose buried below the horizon, the third problem recognized was the inability to stop the nose at the 180 degree point on the horizon. To even attempt this

required the pilot to look over his shoulder and mentally draw a line from that point to the nose of the aircraft. Precise tracking could not be performed at the completion of the maneuver and any references in the HUD that might have been used for the 105 mil capture could not be used.

The F-15C/D simulator produced slight wing rock in both configurations that was controlled by the use of coordinated rudder. Initially the wing rock posed problems since application of rudder tended to aggravate the situation. But, after practice, the correct inputs were determined and the rudder damped the oscillations.

In general the flight test technique was found to require extensive pilot compensation and the results were not repeatable from one run to the next.

During this testing two questions of significant importance arose. What is the best turn capability for the aircraft and what flight conditions satisfy this? As discussed in section IV.3 the aircraft could be either flown at the maximum g limit, the maximum AOA limit, on the aircraft limiter, or at its best turning capability. The last choice is what needs to be determined to use the aircraft to its full capability. To determine this, the aircraft must be flown at several flight conditions. Each of these is listed below:

- * Best sustained turn rate
- * Best instantaneous turn rate
- * Best post-stall turn rate (if it has the capability)
- * A combination of the above

Chapter VII discusses where these flight conditions exist and presents new flight test techniques to quantify this data.

VI.2. Axial Agility Testing

The flight test technique used to perform the axial agility testing was found to be easy to perform and repeatable. Although the simulator did not produce great outside references, the flight test technique was still satisfactory.

VI.3. Roll Agility Testing

During roll agility testing one problem was noticed that caused concern. When attempting to arrest the roll rate, large overshoots occurred (at times 90 degrees past the desired capture point). This was the biggest problem at the high airspeed low load factor test points. As load factor was increased, the ability to capture following the 180 degree roll change became easier, but still required extensive pilot compensation. This problem could have been caused by the F-15C/D flight control laws and should be attempted on other aircraft to verify the repeatability of the flight test technique.

Coupling, as expected, was experienced during the roll but was not a problem at the flight conditions tested. The overall FTT appeared to be satisfactory other than the aforementioned problem.

VII. Flight Test Procedures and Equipment

From the previous section, it was seen that the pitch agility testing was found to be difficult and unrepeatable. The major questions of what is the best turn capability of the aircraft and what flight conditions satisfy this were unanswered. The tests performed in this section were limited to an evaluation of pitch agility only and attempts to answer these questions. An A-37B aircraft was used to perform the testing due to its ability to maneuver in the post stall arena. The tests were conducted at the Air Force Flight Test Center, Edwards AFB, California from 17 October to 4 November 1990 as part of the USAF Test Pilot School (USAFTPS) curriculum. A total of 8 sorties were flown for 9.7 hours. The flight test techniques used during this evaluation were revised using lessons learned from the simulator results. The objective of this evaluation was to develop repeatable pre-stall and post-stall flight test techniques that measure pitch agility. The specific test objectives were:

1. Determine the angular reserve of the A-37B as a function of calibrated airspeed or load factor at the lift limit.
2. Determine the maximum controllable post-stall heading change of the A-37B as a function of calibrated airspeed.
3. Using a 180 degree turn, compare the sustained turn performance with pre-stall and post-stall agility techniques.
4. Evaluate the repeatability and validity of the agility FTTs.

These specific objectives relate to the previously discussed flight conditions. The sustained turn capability of the A-37B was verified during the flight testing and is presented in the results. The lift limit of the A-37B is a measure of the best instantaneous pre-stall turn capability of the aircraft during changing flight conditions. The angular reserve, (the maximum heading change the aircraft can generate before slowing to a turn rate equal to or less than the maximum pre-stall turn rate) is the measure of post-stall turn rate the aircraft can generate at a specific pre-stall flight condition. Finding these three conditions will determine what the best turn capability of the aircraft is and which combination of these maneuvers should be used to achieve this.

VII.1. Flight Test Equipment

The A-37B, manufactured by the Cessna Aircraft Company was an all metal, low wing, jet attack and counter-insurgency aircraft with side by side seating and dual center stick controllers. The aircraft was powered by two General Electric J85-17A axial flow, non-afterburning turbojet engines of approximately 2350 pounds thrust each (standard day, sea level, maximum). The reversible, purely mechanical flight control system actuated a conventional elevator, ailerons, and rudder. Other equipment included a two position speedbrake, spoilers, thrust attenuators, ejection seats, oxygen system, 90 U.S. gallon wing tip fuel tanks, and four armament pylons under each wing. Figure 15 is a drawing of the aircraft. A complete description of the A-37B is contained in the Flight Manual [6:1-1].

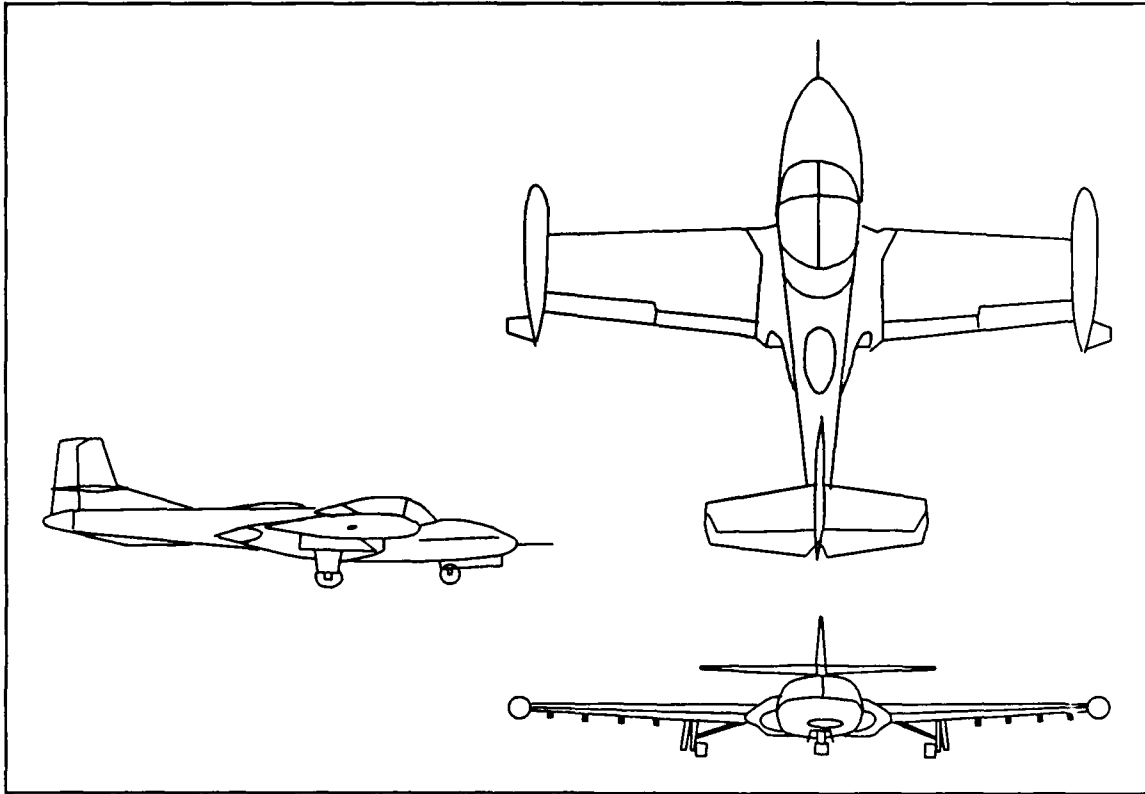


Figure 15. The A-37B Dragonfly

Flight control characteristics of the A-37B at high angles of attack made it suitable for post-stall investigations. Stall warning was characterized by obvious airframe buffet. In accelerated stall entries, warning occurred approximately eight knots above the stall speed. Aileron and elevator control remained effective through approach to and into the stall. Stall was indicated by a series of bucking motions as the aircraft angle of attack oscillated above and below stall. Recovery from a stall was easily achieved by reducing back pressure or applying forward pressure on the stick [6:6-2].

All sorties were flown using A-37B serial numbers 70-0790, and 73-1090, which were part of the general support fleet at Edwards AFB. A-37B 73-1090 was equipped with a pulse code modulation (PCM) data acquisition system (DAS) with an on-board magnetic tape recorder and telemetry capability. The sample rate was 8 per second. Table 5 shows the accuracy of the parameters of interest for this test. A

Table 5. DAS Parameters of Interest

PARAMETER	ACCURACY	PARAMETER	ACCURACY
AIRSPPEED (kts)	4.0	ATTITUDE	
		pitch (deg)	1.0
NORM ACCEL (g)	0.1	bank (deg)	2.0
AOA (deg)	1.0	ANGULAR RATE	
		pitch (deg/sec)	1.0
TIME (sec)	0.01	roll (deg/sec)	2.0
		yaw (deg/sec)	1.0
CONTROL DEFL.			
LONG. (in)	0.2	FUEL USED (gal)	1.0

complete description of the DAS is in the Instrumentation Handbook [19:33]. This equipment did not affect the performance or flying qualities of the aircraft.

VII.2. Flight Test Procedures

Pitch agility testing began with collecting sustained turn performance data and the lift limit determination at 20,000 feet pressure altitude and 89% power. Post-stall

investigations were then made to determine how much heading change (angular reserve) could be achieved with a rapidly applied full aft stick deflection at four entry load factors (2.0, 2.5, 3.0, 3.5 g). The test team also evaluated the pitch tracking ability at the completion of these post-stall conditions. Testing was performed between 18,000 and 22,000 feet pressure altitude. Maximum load factor seen during the tests was 4.3 g. Minimum test load factor was 0.0 g. All testing was done at 89% power to minimize the possibility of engine instabilities in the post-stall regime. Both quantitative and qualitative data were collected to evaluate the different agility FTTs. DAS parameters in Table 5, were recorded for each maneuver. Qualitative data consisted of pilot comments about the FTTs. These comments were compared and correlated to the quantitative data in order to refine and validate the final FTTs.

Load factor was standardized to a weight of 8,800 pounds. Aircraft weight ranged from 9,800 pounds to 7,800 pounds during testing. Center of gravity moved from 26.1% MAC to 25.0% MAC during flight. USAFTPS software and strip charts were used for sustained turn data reduction [20]. Off the shelf spreadsheet applications running on personal computers were used to calculate rate of heading change from pitch and yaw rates through Euler angle transformations. Appendix E describes the data reduction methods.

VII.2.a. Lift Limit. The lift limit line was found using 89% power due to engine instabilities above this power setting. Starting from trim at 200 knots indicated airspeed (KIAS) and 20,000 feet pressure altitude, power was set to 89% on both

engines and allowed to stabilize as the aircraft accelerated to approximately 230 KIAS in level flight. Approaching 230 KIAS the aircraft was rolled into a left hand level turn and load factor was smoothly increased at a rate of approximately 1 g per second until moderate buffet and a slight bucking motion was felt on the aircraft. This was the lift limit as defined in the Flight Manual [2]. Airspeed was then allowed to decrease as moderate buffet was maintained. The maneuver ended when the aircraft stabilized at about 140 KIAS and 2.0 g ($P_r=0$). Figure 16 graphically illustrates this maneuver.

VII.2.b. Angular Reserve. Angular reserve was measured by flying the maneuver for the lift limit line determination until reaching a target load factor of 2.0, 2.5, 3.0 or 3.5gs. Upon slowing to the target load factor (± 0.2 g) full aft stick was applied in less than one second ("stick snatch"). The stick was held full aft until the rate of heading change decreased to below the lift limit turn rate. The pilot then eased the stick forward and recovered the aircraft. The target load factors were flown in order starting at 2.0 g and increasing to 3.5 g during each flight.

VII.2.c. Maximum Controllable Heading Change. Once the angular reserve was determined, an investigation was performed to find the maximum heading change through which the A-37B had adequate pitch pointing ability. Adequate pitch pointing ability was defined as the ability to maintain a point on the horizon within 105 mils (3 degree field of view) longitudinally for 1 second using the reticle in the production

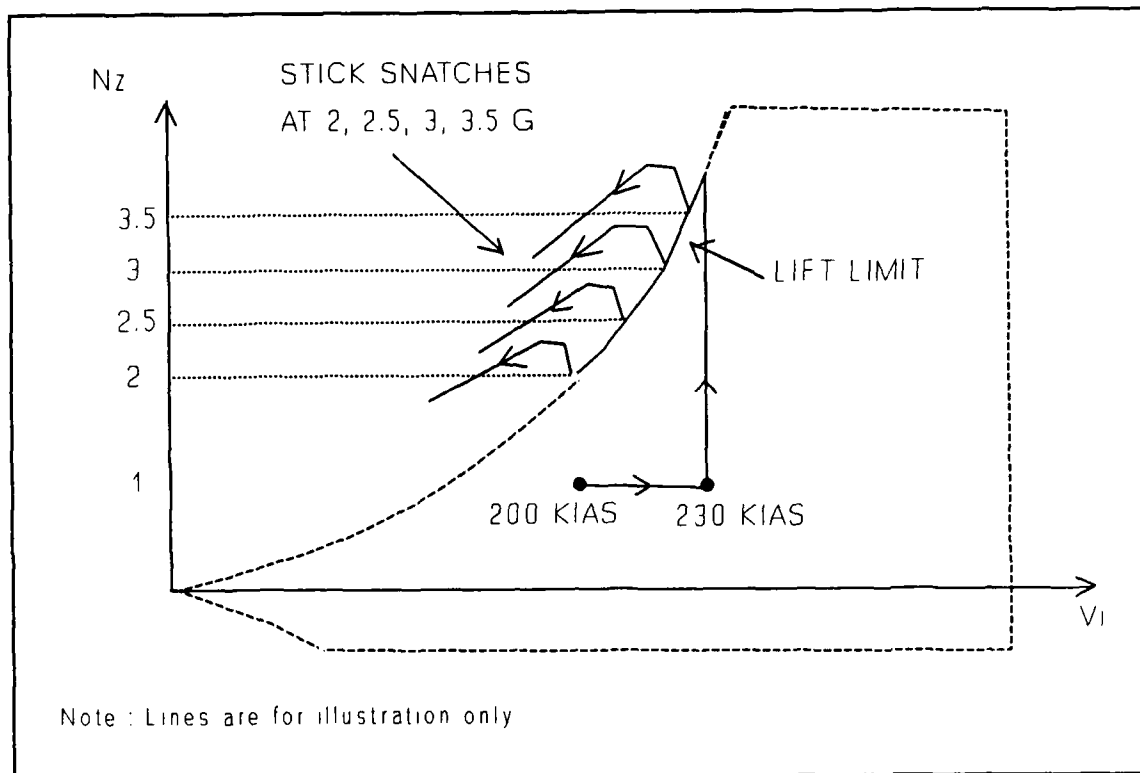


Figure 16. Lift Limit Line and Angular Reserve Maneuver

gunsight.

The maneuver was identical to the angular reserve investigation through the stick snatch. After holding full aft stick for a predetermined delay, the pilot unloaded the aircraft and tried to track a point on the horizon. Test points flown were 2.0, 2.5, 3.0, and 3.5 g entry load factors on the lift limit. The delays between the snatch and initiation of tracking were 0.5, 1.0 and 2.0 seconds at each entry load factor.

VII.2.d. Time to Turn 180 Degree. A flight test technique was developed to measure the advantage gained by maneuvering in the post-stall regime. This FTT was

designed to compare pre-stall and post-stall agility of the aircraft. The FTT compares the time required to turn through 180 degree using three different turn profiles. At the completion of the turn, the pilot is required to track a point on the horizon within 105 mils for one second, simulating a missile shot. If the point could not be maintained within the given tolerance, the maneuver was considered invalid. The one second tracking time **should not** be included in the time to turn 180 degrees. The three turn profiles are listed below:

1. Stabilized Turn (pre-stall): Stabilize the aircraft in a max sustained turn at the test airspeed. When stabilized, begin timing through 180 more degrees, noting elapsed time as soon as the 180 degree point is reached. Track the point as described above.
2. Lift Limit Turn (pre-stall): Stabilize the aircraft in a max sustained turn at the test airspeed. When stabilized, begin timing, immediately pull to the lift limit, and turn through 180 more degrees on the lift limit. Note elapsed time as soon as the 180 degree point is reached, and track that point.
3. Lift Limit / Post-stall Turn: Stabilize the aircraft in a max sustained turn at the test airspeed. When stabilized, begin timing and immediately pull to the lift limit. When the point is reached at which the remaining heading change equals the angular reserve, instantaneously pull the stick full aft (stick snatch), then track the 180 degree point once it is reached. Note elapsed time as soon as the 180 degree point is reached.

The turn is always begun from a stabilized level turn in an attempt to minimize differences between pilots for time required to roll into the turn and stabilize at the stated condition.

VIII. Flight Test Results and Analysis

All flight test techniques used to obtain the pitch agility data were found to be valid and repeatable. The A-37B had an angular reserve of up to 40 degrees and pitch tracking was possible within 105 mils. A comparison between the time to turn 180 degree using a sustained turn, a turn at the lift limit, and a turn using both lift limit and post-stall excursion was planned but not accomplished because sorties were not available. An analysis of the time to turn 180 degree FTT at three entry airspeeds was done using data from the other FTTs.

VIII.1. Flight Test Results

The original power setting described in the test plan was 90% engine RPM. After several engine rollbacks at this power setting due to sideslip induced on the aircraft, the power was reduced to 89%. No further engine problems occurred. All the flight test techniques described below were flown at 89% engine RPM.

VIII.1.a. Lift Limit. A V-N diagram of the lift limit line and each stick snatch is shown in Figure 17. The flight test lift limit line closely approximated that in the Flight Manual.

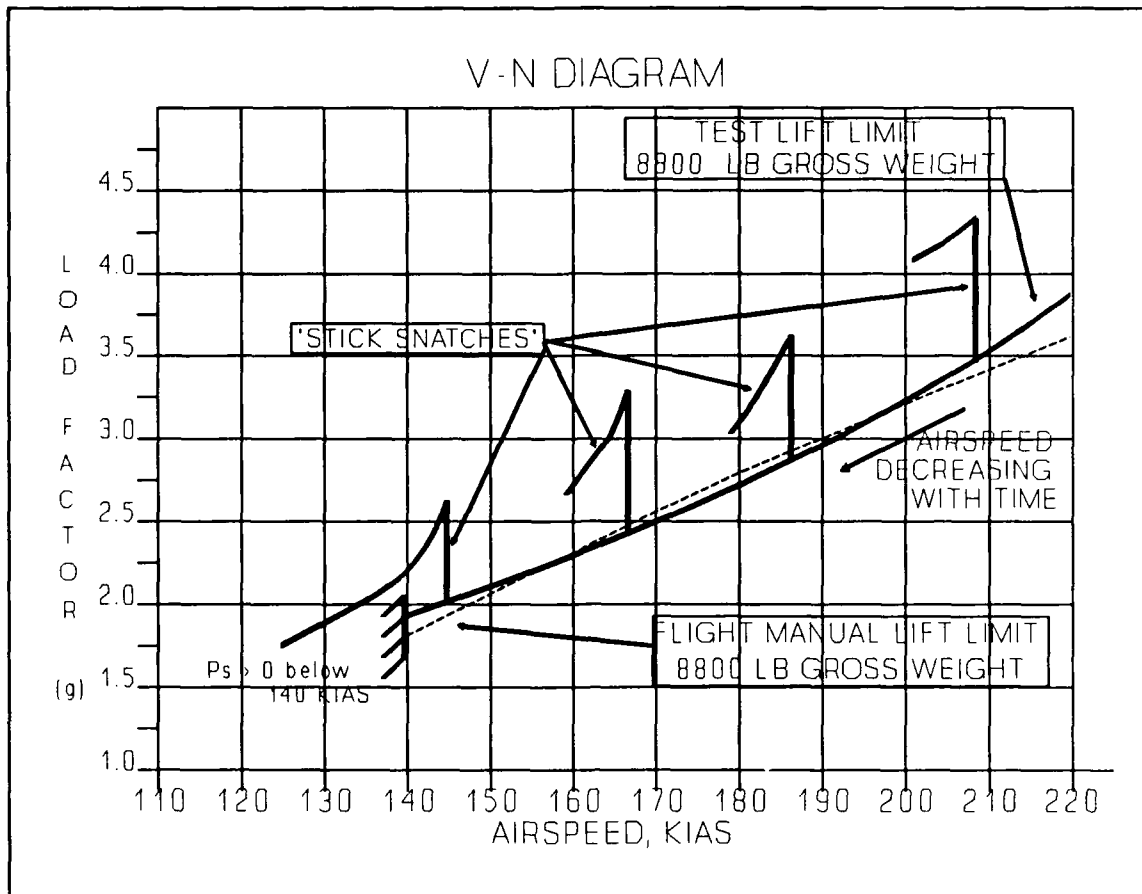


Figure 17. A-37B V-N Diagram

VIII.1.b. Angular Reserve. Table 6 presents the angular reserve of the A-37B. Representative time histories are contained in Appendix F. The angular reserve of the A-37B increased with decreasing entry airspeed. This was an unexpected result as was probably caused by the dynamic modes of the A-37B, although this cannot be confirmed. A maximum overshoot of 0.75 g was seen during the angular reserve testing. The load factor overshoots indicate that the lift limit may not correspond to $C_{L_{max}}$ in the A-37B. At a starting load factor of 2gs the angular reserve was 40 degrees. This was the largest angular reserve recorded for this test. The smallest

Table 6. Angular Reserve Summary

Target Load Factor (g)	Airspeed (KIAS)	Average Heading Change (deg)	Maximum Turn Rate (deg/sec)	Elapsed Time (sec)	Number of Test Points
2.0	140	40	55	1.2	3
2.5	170	35	50	1.1	2
3.0	191	32	50	1.0	3
3.5	209	19	45	0.7	2

angular reserve, obtained at 3.5gs, was 19 degrees. Figure 18 shows the relationship between starting load factor and the amount of angular reserve the A-37B obtained. Aileron inputs to counter the right sideslip due to the left turn varied with entry load factor. The aileron inputs required did not make the *FTT* unrepeatable from pilot to pilot, but did require some practice.

VIII.1.c. Maximum Controllable Heading Change. The pilot was able to attain adequate pitch pointing capability for all entry load factors and time delays. As a result, the entire angular reserve of the A-37B was controllable. Figure 18 represents the effect of load factor on maximum controllable heading change as well as the angular reserve. A total of 21 test points were flown to verify the controllability. Tracking within 105 mils was possible following the stall.

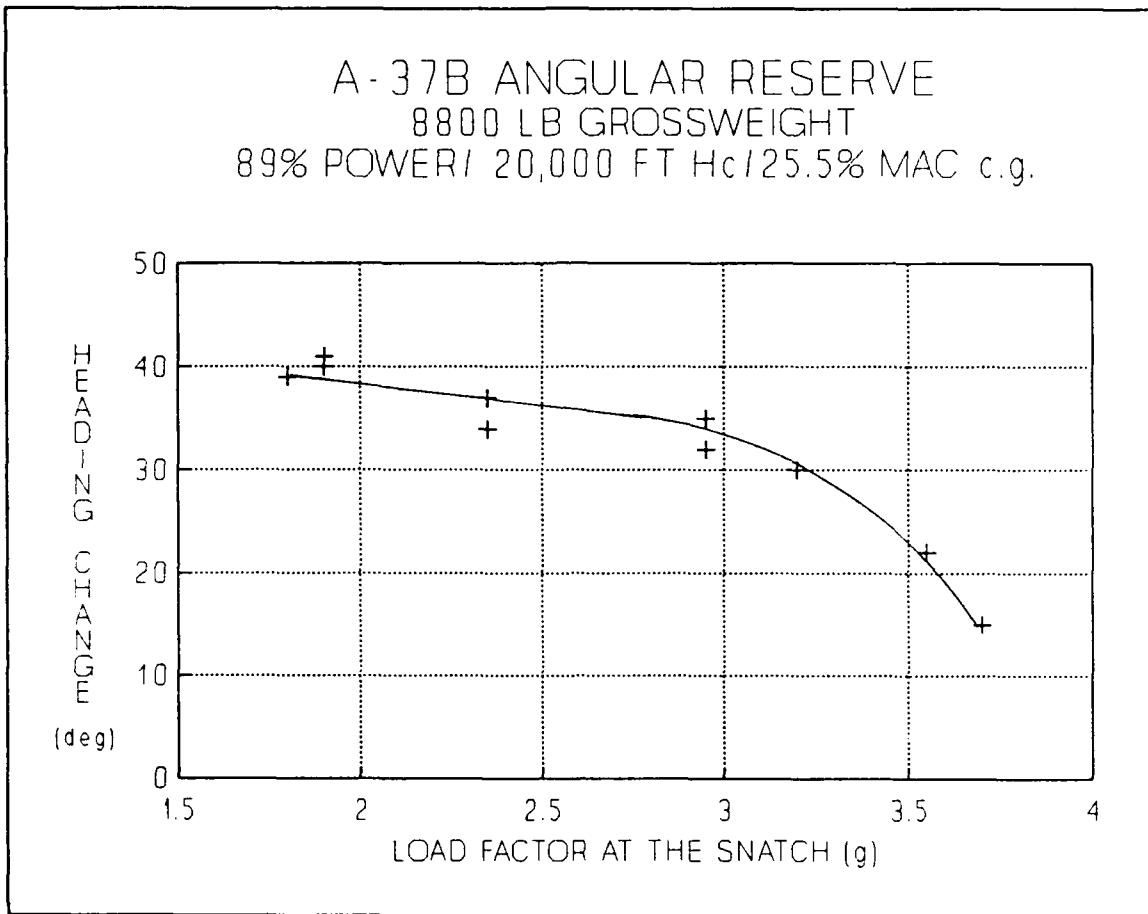


Figure 18. A-37B Angular Reserve

The quality of tracking was a function of the entry load factor. At 3.5 g with 0.5 second delay, pilot compensation was the most intense of all points tested. Tracking accuracy was ± 50 mils. At 2.0 g and 0.5 second delay, tracking accuracy was ± 5 mils and pilot compensation was not a factor. As the energy state at entry increased, so did the pilot compensation required to attain accurate tracking.

Tracking accuracy was also a function of the delay between the snatch and initiation of tracking. For a given entry load factor, a longer delay resulted in

improved tracking accuracy. This effect was more pronounced at high entry load factors. Delaying initiation of tracking until the full angular reserve was obtained gave the best tracking results and optimum post-stall turn capability of the aircraft. The time histories in Appendix F show that the full angular reserve obtained depended on the entry condition. At the lower g levels a delay of at least one second was required to achieve this condition while at the 3.0 and 3.5 g levels only 0.75 seconds was required.

VIII.1.d. Time To Turn 180 Degree. Using the previously gathered lift limit, angular reserve and maximum controllable heading change data, 180 degree turns can be constructed to compare different techniques to complete the turns. This simulation assumes instantaneous transition from sustained turn conditions to the lift limit, and that the proper angular reserve lead point was determined. Starting airspeeds of 150, 180, 210 KIAS were examined. At 150 KIAS, a 180 degree turn on the lift limit took approximately 20 seconds, as did the sustained turn at this airspeed. At the end of the lift limit turn, there was an 8 KIAS airspeed loss. Using post-stall agility, however, the 180 degree turn took only 16 seconds, 20% less than the pre-stall techniques. The airspeed penalty for using this technique was negligible as shown by Figure 19. The turns accomplished at the higher airspeeds depicted in Figures 20 and 21 showed similar results. A larger difference between the sustained turn and the lift limit turn initially reduced the time significantly, but a larger loss of airspeed was also seen (up to 35 KIAS during the 210 KIAS entry). The post-stall technique

reduced the time to turn 180 degree by another two seconds or 12%, without a significant airspeed penalty. These FTTs should be flown to verify the repeatability of the technique and accuracy of the data.

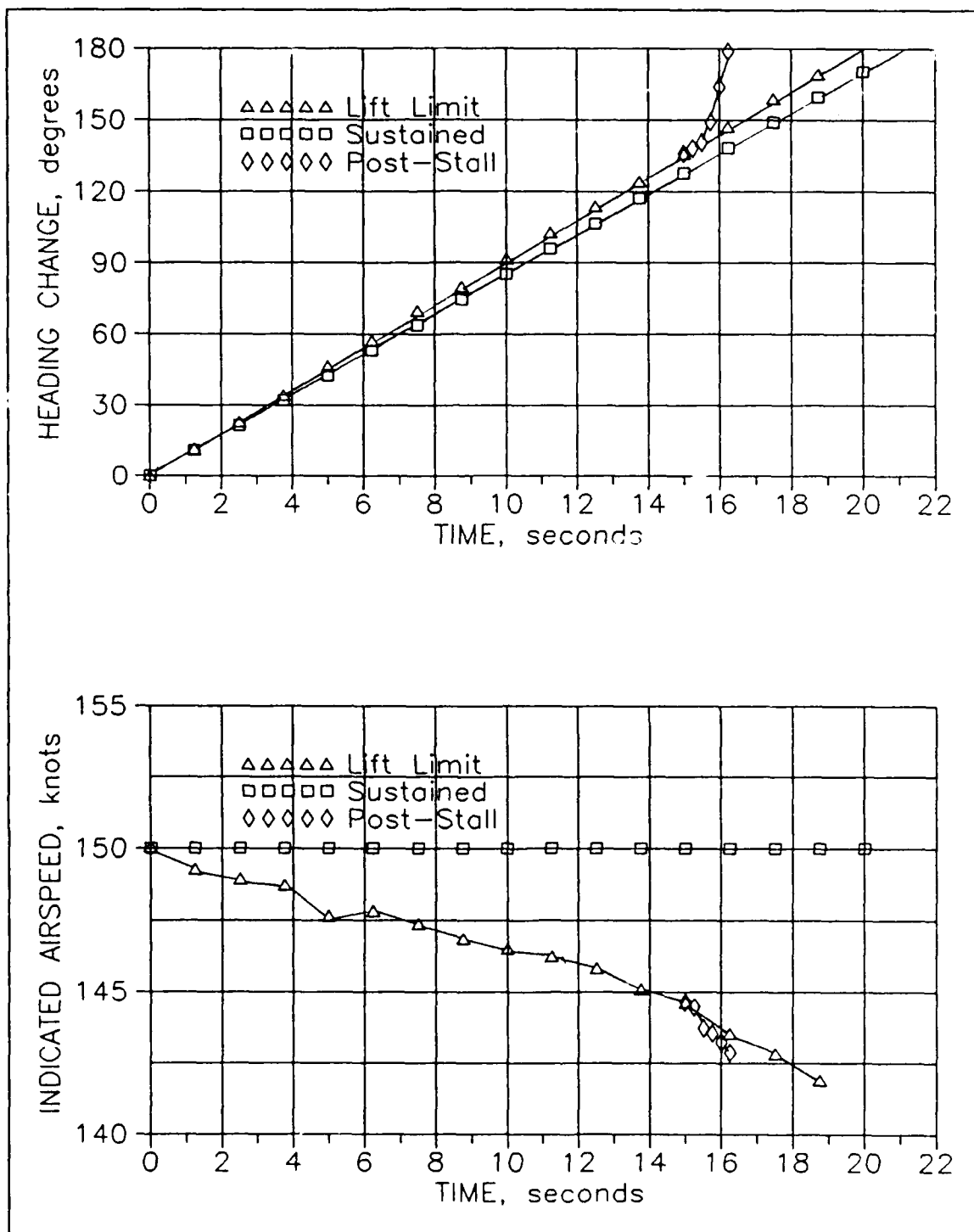


Figure 19. Time to Turn 180 Degrees, 150 KIAS Entry Airspeed

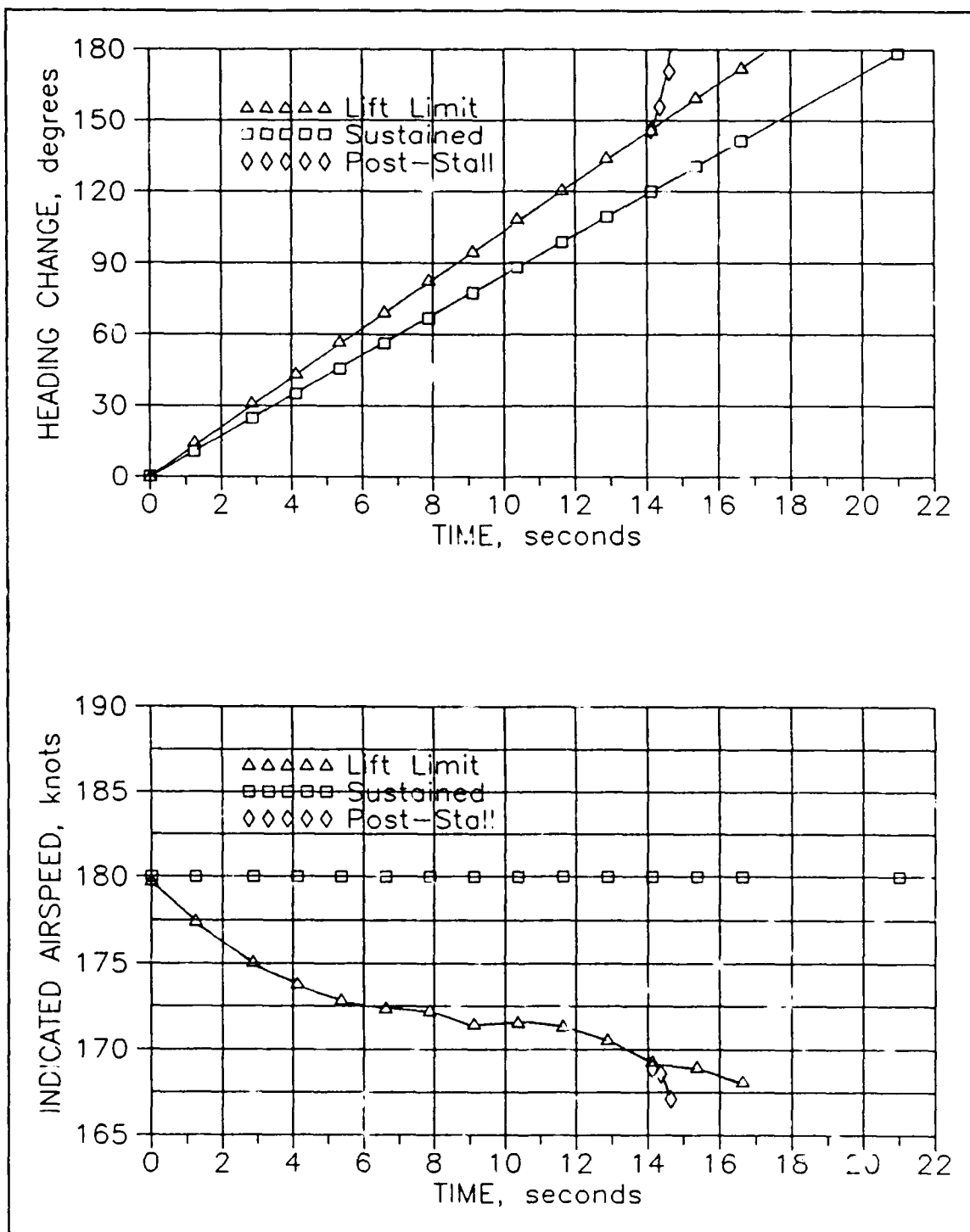


Figure 20. Time to Turn 180 Degrees, 180 KIA^s Entry Airspeed

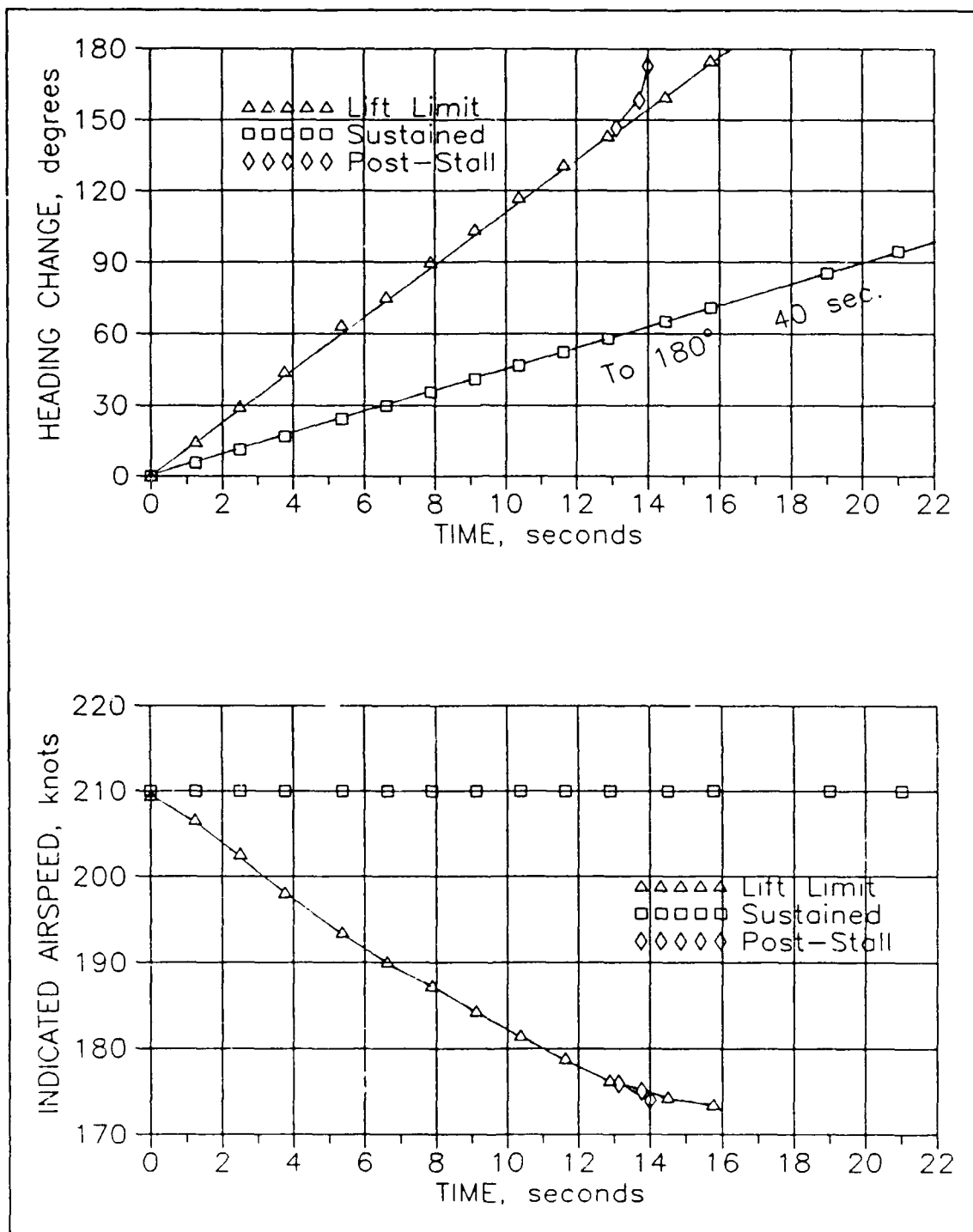


Figure 21. Time to Turn 180 Degrees, 210 KIAS Entry Airspeed

VIII.2. Flight Test Technique Analysis

VIII.2.a. Lift Limit. The lift limit of the A-37B was defined not at a specific angle of attack (AOA), but as the point where moderate buffet and slight bucking motions occurred. The lift limit did not coincide with C_{Lmax} for the wing. The aircraft developed a series of bucking motions that were easily recognized. Flying at this limit was very repeatable.

The original method for determining this condition was to start from trim conditions of 200 KIAS at 20,000 feet pressure altitude and accelerate to 250 KIAS in level flight. Approaching 250 KIAS, the aircraft would be rolled in approximately 70 degree of left bank, and a load factor of 5gs would be captured in a level turn. Airspeed would be allowed to bleed until the aircraft reached a target AOA. The target AOA would be maintained in a level turn as airspeed and load factor decreased. Target AOA would start at 13 degrees and would be increased in 1 degree increments until reaching stall indications. The AOA where stall indications were seen would be considered the lift limit.

Thirteen degrees AOA was chosen because of the known 1 g stall condition of approximately 15 degrees AOA determined during A-37B spin testing in the USAFTPS curriculum.

The first problem in actual flight test, was the inability of the A-37B to accelerate to 250 KIAS at 89% RPM and 20,000 feet pressure altitude. The aircraft would sustain a maximum of 230 KIAS in level flight. Next, when the load factor was applied in an attempt to reach 5 g, the aircraft would only obtain approximately

3.7 g before stall indications were felt. The angle of attack during these stall indications was only 5 to 6 degrees. As the airspeed and load factor were allowed to bleed off following the lift limit, the AOA continued to increase to 11 to 12 degrees at the 140 KIAS and 2 g point. The maneuver was terminated at this point because P_z was zero. Since the AOA changed during this maneuver, the constant AOA method could not be used. The technique described above was flown at several different fuel weights and the results were found to be very repeatable. This "seat of the pants" feel the aircraft generated at the lift limit was easy to fly, and the results compared well with flight manual predictions.

Although the constant AOA method did not work in the A-37B, aircraft that maintain a constant stall AOA would most likely perform well using the original technique.

VIII.2.b. Angular Reserve. For angular reserve testing the maneuver for lift limit determination was flown to a target load factor. Initially, these load factor were 2.0, 3.0, 4.0, and 5.0gs. When the aircraft would not obtain either 4.0 or 5.0gs, the target load factors were decreased to 2.0, 2.5, 3.0, and 3.5gs. Either load factor or airspeed could be used to determine target conditions. With the sensitive g-meter in the A-37B, the load factor was the easiest to track repeatedly. At the target load factor, full aft stick was applied rapidly (stick snatch) and held until the observed turn rate was less than the lift limit turn rate. These turn rates were determined by analysis of real time strip chart data.

The maneuver was flown as described above with slight modifications to prevent excessive sideslip build up. At the higher load factors (3.5 and 3.0) immediately following the stick snatch, a large yawing moment to the right was produced causing blanking of the right engine and a right roll. Over 20 degree of sideslip was generated during these maneuvers. The sideslip was thought to be due in part to the engine gyroscopic effects. To counter this yaw, left aileron was input in an attempt to reduce the excessive sideslip build up. Initially aileron was applied following the stick snatch. This technique did not work well because the yaw rate had already started to build. Next, aileron was incorporated into the stick snatch. This technique gave the best results and felt natural to the pilots. The aileron input was successful in countering the yaw and reducing sideslip below 10 degree. If the aileron input had not worked, the next step would have been to use bottom rudder to produce the same effect. The aileron was chosen due to the ability of the pilot to fine tune the aileron inputs with his hands rather than attempting to repeatably counter the yaw with his feet. Once the pilot had flown the maneuver two to three times, he was able to consistently apply the correct amount of aileron and produce repeatable angular reserve results.

VIII.2.c. Maximum Controllable Heading Change. This portion of the test was used to determine the amount of heading change that could be obtained while the aircraft remained controllable for the tracking task. The tracking task consisted of capturing a point on the horizon within 105 mils and holding the aircraft there for one

second. The 105 mil criteria was used to simulate a 3 degree field-of-view missile seeker head. The standard reticle on the A-37B was used to judge the capture. The flight test technique used to perform this capture was identical to the flight test technique used for angular reserve testing through the stick snatch. Following the stick snatch, the input was to be held for one second and increased in one second intervals until the aircraft became uncontrollable.

The flight test technique worked as stated above but the time intervals were reduced to 0.5, 1.0, and 2.0 seconds since the full angular reserve of the aircraft was always obtained in less than 2 seconds. Initially the pilots had problems stopping the nose of the aircraft without an extensive unload and pitch oscillation. The reason for this un-commanded motion was found to be too much forward stick movement to stop the aircraft. The amount required to keep the aircraft controllable was only about 1/2 to 1 inch of forward travel. When this stick motion was incorporated into the technique, the entire angular reserve was found to be controllable. The higher the entry load factor, the less forward stick was required to stop the pitch rate and capture a point on the horizon. A tighter capture criteria could be attempted to determine the limits of controllable tracking.

VIII.2.d. 180 Degree Turns. These turns were not flown during this test due to sortie non-availability, and therefore there are no lessons learned for the flight test technique.

IX. Conclusions and Recommendations

Development of the agility metrics incorporated past lessons learned by the agility community and were designed to be easily interpreted by operational pilots. The metrics proposed in this study meet this goal, but also have great application to engineers and threat analysts alike.

The flight test techniques proposed initially were the outcome of lessons learned during previous testing. Although some of the original procedures did not satisfy the repeatability requirement imposed, the final product, after development during testing, meets this requirement. The simulator results raised some question about the roll agility flight test technique. Whether the problems found actually showed agility problems with the simulator configuration or problems with the flight test technique itself are not known. Flight testing should be performed to verify the validity of the roll agility technique. These same flight test techniques should be performed using other aircraft to verify the validity and repeatability of the techniques.

Flight testing was performed on pitch agility techniques only due to the limited resources and time provided. During this testing, it was found that the A-37B stall angle of attack varied with airspeed. Bucking motions near the stall were easily felt and did not significantly effect the data.

During angular reserve testing, pilot compensation was minimal during the lower g test points. At higher g entries, pilot compensation was necessary, making the FTTs more difficult. This compensation consisted of aileron inputs to reduce sideslip excursions. With practice, the inputs became very repeatable. The need for control inputs to prevent sideslip may be unique to the test aircraft. Flight control systems with feedback designed to prevent sideslip may not require this type of pilot compensation.

The angular reserve of the A-37B increased with decreasing entry airspeed. The entire angular reserve of the A-37B was controllable to within 105 mils (3 degree field of view).

The time to turn 180 degree FTT was not flown. The FTT was designed to compare pre-stall to post-stall agility techniques. A analytical analysis of the FTT indicated a potential time advantage of up to 20% during a 180 degree turn using post-stall agility techniques. The time to turn 180 degree FTTs should be flown to verify the repeatability of the technique and accuracy of the analysis.

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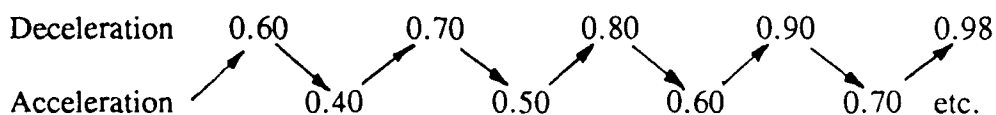
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Appendix A: Axial Agility Flight Test Techniques

Agility Evaluation of the RF-4C and T-38A Aircraft, "Have Agile", 2 June

1986. "Axial agility was determined using a sequence of accelerations and decelerations to determine the specific power onset rate at load factors from 0 to 4g for the T-38A and from 0 to 6g for the RF-4C. Accelerations were initiated from idle power with the speed brakes open and decelerations were initiated from maximum power with the speed brakes closed. For load factors of 1g and greater, the air craft was accelerated at the desired load factor to the initial target Mach number. When the target Mach number was reached the throttles were snapped to idle and the speed brakes opened to begin the deceleration. The deceleration at the desired load factor continued until a target Mach number was reached where the throttles were snapped to maximum power and the speed brakes closed to begin another acceleration. The sequence of accelerations and decelerations was continued until the data band at the test altitude and g loading was completed. For example, the Mach number sequence used at 10,000 feet Hc and 1g was:



.....This procedure was repeated until the required data points had been accomplished." [17:17-18]

Appendix B: Turn/Pitch Agility Flight Test Techniques

T-38/F-16B Agility Metrics Evaluation, "Agile Lightning", 9 December 1987.

"A military power acceleration was performed to the test airspeed. At the test airspeed, a rapid pull-up at the test g limit was performed to the target pitch angle. The maximum load factor used was 5 g for the T-38A. For the F-16B, the maximum load factor for wings level maneuvers was 7.3 g's. A maximum of 5.5 g's was used for the banked pull-ups due to the possibility of rolling g induced by the roll sensitivity of the aircraft. For the low dynamic pressure points, the load factor used was limited by moderate buffet in the T-38A, and by the angle of attack (AOA) limiter in the F-16B. The pull-up was started when crossing the top of the data band for the 30 and 45 degree nose down FTTs and at the bottom of the altitude band for the 0 to 60 degree FTT. For a build-up approach and FTT practice, 15 to 15 degree pitch angle changes were flown prior to the 30 to 30 and 45 to 45 degree FTTs. A variation of this FTT was performed by flying a constant altitude 90 degree heading change break turn using symmetric g limits."[22:13]

RF-4C/F-16B Agility Metrics Evaluation, "Agile Thunder", December 1987.

"The FTT used to measure pitch agility was flown in the vertical plane only because heading was not recorded by the data acquisition system (DAS). Starting from the

initial pitch attitude, at the specified airspeed and altitude, a wings level pull was executed at the test limit load factor or angle of attack to attain the final pitch attitude. The initial pitch attitude was below the horizon and the final condition was a nose high attitude of the same magnitude as the initial dive. However, the - 45 degree to + 45 degree maneuver was subsequently modified to start from level flight. This was done because of the difficulty encountered in trying to consistently set up the maneuver and because it was thought to result in a more operationally significant maneuver. Precision was included in the maneuver by requiring the final pitch angle be maintained within one degree of the specified condition.

The airspeed and altitude tolerances applied only to the initial condition. Military power was used for all maneuvers."[21:13]

F-15B Agility, "Have Agile Eagle", 5 June 1989. "The objective of this maneuver is to capture a 180 degree heading change while in a level turn in minimum time. Initial/ final energy states and time to capture final conditions will be measured. Stabilize within initial altitude and airspeed tolerances in wings level flight. Roll at 1.0 g then pull to 6.0 g maximum, to obtain a 180 degree heading change in minimum time in a level turn. Snap the throttles to the desired position (see note below) when starting the roll. Capture the final heading in the minimum time, within tolerance, and maintain that heading angle for at least one second.

note: After start of timing, if above corner velocity (dependant upon altitude, configuration, etc.), snap the throttles to idle and extend the speedbrake. Upon slowing to 20 to 30 KCAS above corner velocity, snap to maximum A/B (afterburner) and retract the speedbrake. If below corner velocity at start of timing, snap the throttles to maximum A/B at the maneuver initiation. Note, special attention must be paid to engine response when snapping the throttles to maximum A/B at the 200 KCAS test points.

200 KCAS:

The quickest turn is accomplished by pulling the aircraft to optimum AOA (approximately 25-30 units in the F-15). This minimizes the loss in airspeed and allows the pilot to stabilize quicker in the heading capture data band. For capture, quickly release back stick pressure and push slightly forward to nearly 0 g at the desired heading capture point. A slow roll to a wings level attitude will prevent the aircraft from falling out of the altitude data band and make the capture easier.

350 KCAS:

Roll the aircraft and pull quickly to 6.0 gs. When unable to maintain 6.0 gs (after approximately 60 degrees of turn), transition and maintain approximately 30 units AOA. Continue holding this until 45-50 degrees of turn is left to complete. At this time snatch the stick full aft. The timing on the snatch is very critical. If too early, the heading change happens faster, but there is not enough airspeed to quickly capture the heading point. If the snatch is late, capture is easy but time is lost due to a slower heading change. Neutralizing the stick allows an easy heading angle capture.

580 KCAS:

Expect to maintain 6.0 gs throughout the maneuver. The pilot will be required to snap the throttles to idle and extend the speedbrake, and then to snap the throttles to afterburner and retract the speedbrake. Heading capture will be easy at the high airspeed when compared to the slower airspeeds."[18:26]

Appendix C: Rolling Agility Flight Test Techniques

Agility Evaluation of the RF-4C and T-38A Aircraft, "Have Agile", 2 June

1986. "Lateral agility testing was accomplished using loaded rolling maneuvers. The aircraft was established at the target load factor and Mach number in 90 degrees of bank. A slight descent was used to help maintain the desired Mach number. The aircraft was abruptly rolled through 90 degrees of bank to wings level while maintaining the target load factor within 0.2 g. The rolling maneuver was timed from the lateral control input to the point where the aircraft was stabilized within 5 degrees of wings level. A build up approach was used to determine the minimum time to roll while maintaining the load factor and the stopping condition within the data tolerances." [17:27]

T-38A/F-16B Agility Metrics Evaluation, "Agile Lightning", 9 December 1987.

"A military power acceleration was performed up to the test airspeed. When approaching this airspeed, the aircraft was banked at 45 degrees and the desired load factor was established. The aircraft was rolled at a constant load factor to 45 degrees opposite bank. Timing started for the maneuver when the first roll control force was initiated and ended when the aircraft stabilized in the target data band. Rudder was used whenever necessary to coordinate the maneuver and increase the roll rate. For a

build up approach 15 to 15 degree rolls were performed prior to the 45 to 45 degree rolls. In order to stay within the ± 2000 feet altitude band, the maneuver was started below the test altitude. Maximum roll rate compatible with precision and control to stop the aircraft at the target bank angle was used. A limited number of 90 to 90 degree roll reversals were also flown using ± 10 degrees as the tolerance."[22:19]

RF-4C/F-16B Agility Metrics Evaluation, "Agile Thunder", December 1987.

"The proposed roll agility FTT combined the elements of quickness and precision by requiring the pilot to roll the aircraft at various load factors from wings level to 90 degrees (or thirty degrees) as quickly as possible and with enough precision to stabilize at the end condition within 2 degrees. The maneuver began with a shallow dive into the altitude band. Once the altitude and airspeed test conditions were reached, the pilot performed a level pull-up to the normal acceleration test condition. When the proper nz was achieved, the pilot rolled the aircraft to the target end condition and stabilized there for two seconds with a tolerance of ± 2 degrees.[21:22]

F-15B Agility, "Have Agile Eagle", 5 June 1989. "If the initial load factor is 1.0 g, setup for the maneuver in wings level flight. Maintain load factor and airspeed while rolling left to a bank angle of 90 degrees ± 5 degrees. When this roll has stopped, begin the maneuver by rolling over the top (to the right) in minimum time with a pure lateral stick input to capture the desired bank angle. Expect the aircraft to couple during the roll resulting in elevated load factors. Leave throttles in trim

position throughout the maneuver. Capture the final bank angle in minimum time, within ± 5 degrees for at least one second. To set up for the maneuver with an initial load factor greater than 1.0 g, start above or in the top portion of the altitude data band at an airspeed approximately 20 to 30 knots above target airspeed. Roll the aircraft into a 90 degree left bank angle and establish the desired elevated load factor. At 90 degrees of bank, the aircraft will descend into the data band naturally. This will give the pilot time to concentrate on modulating the power to establish the target trim airspeed. When all data band tolerance are met, the desired loaded roll can be initiated."[18:30]

Appendix D: Simulator Description

The flight simulator used in the testing of the designed agility flight test techniques was the LAMARS (Large Amplitude Multimode Aerospace Research Simulator). "The LAMARS provides a full compliment of high quality flight cues for fighter aircraft system evaluation. The simulator consists of a five degree-of-freedom beam type motion system which carries a single place fighter cockpit and spherical dome display system on the end of a 30 foot beam.

The cockpit can be configured to represent the front seat of current and proposed fighter aircraft. A modular cockpit design (with instrument panel sections, side consoles, and controllers that are easily removable) has been developed to permit quick change between configurations. Complete changeover to another configuration takes less than an hour. Available hardware for the LAMARS cockpit includes conventional flight and engine instruments, cathode ray tubes, caution and warning lights, radar warning receiver control and display, a McFadden programmable center stick, side controllers, single and dual quadrant throttle, an F-18 HUD (heads-up display) focused at the screen, an infinity focus wide-field-of-view LANTIRN HUD, and an AIC-18 communication system typically used for voice communication, engine sound, and voice warning.

The LAMARS visual display system utilizes a 10 foot radius, spherical projection screen on which a sky-earth projector and a servoed target projector provide a visual representation of the outside world. The screen provides a 266 degree horizontal field-of-regard and approximately a 108 degree vertical field-of-regard as seen in Figure 22. The target projector provides a monochromatic, selectable line rate (525, 875, and 1023), 15 or 60 degree diagonal field-of-view visual scene. For air-to-air combat and formation tasks, a wire-support target model is used in

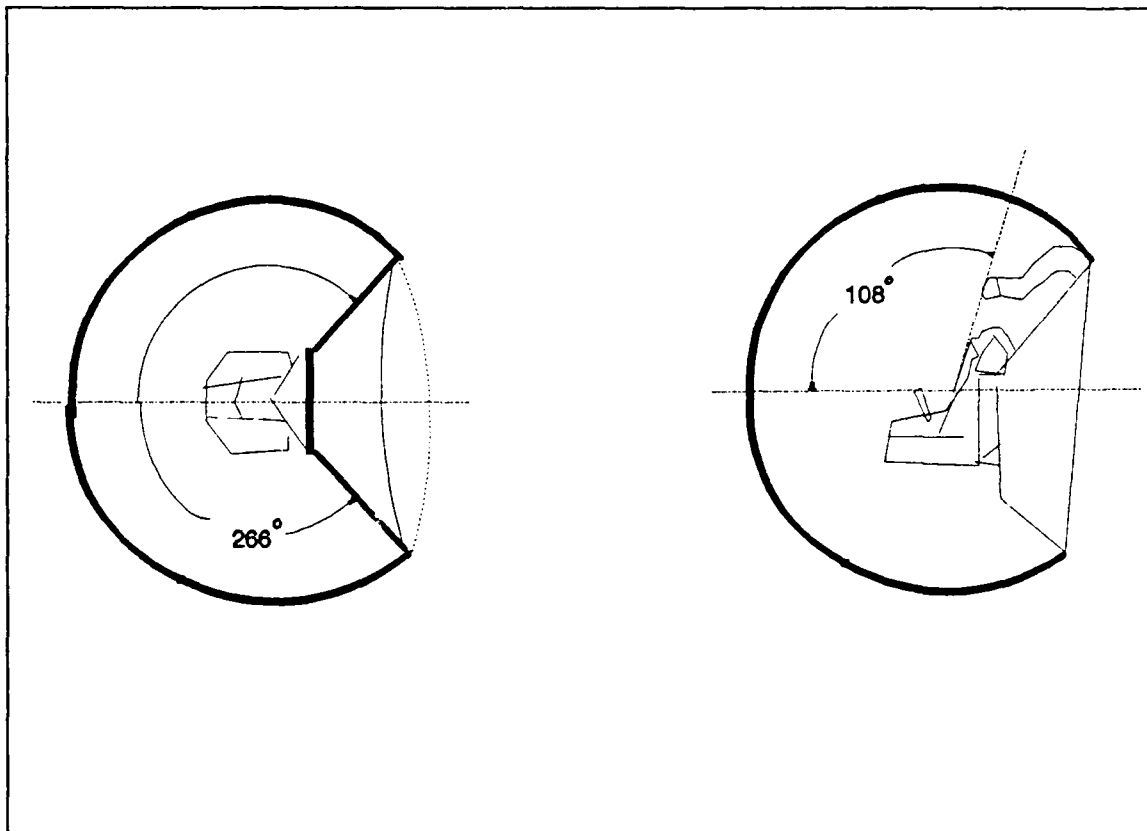


Figure 22. Visual Display Field-of-Regard

conjunction with the 15 degree lens and 1023 line rate to achieve a 400 foot to 47,600 foot range for aircraft detection and tracking. For air to surface tasks, the terrain board system is used with the 60 degree lens (36 degree vertical by 48 degree horizontal). The target projector can be driven aircraft fixed, target fixed, or by a helmet tracking system.

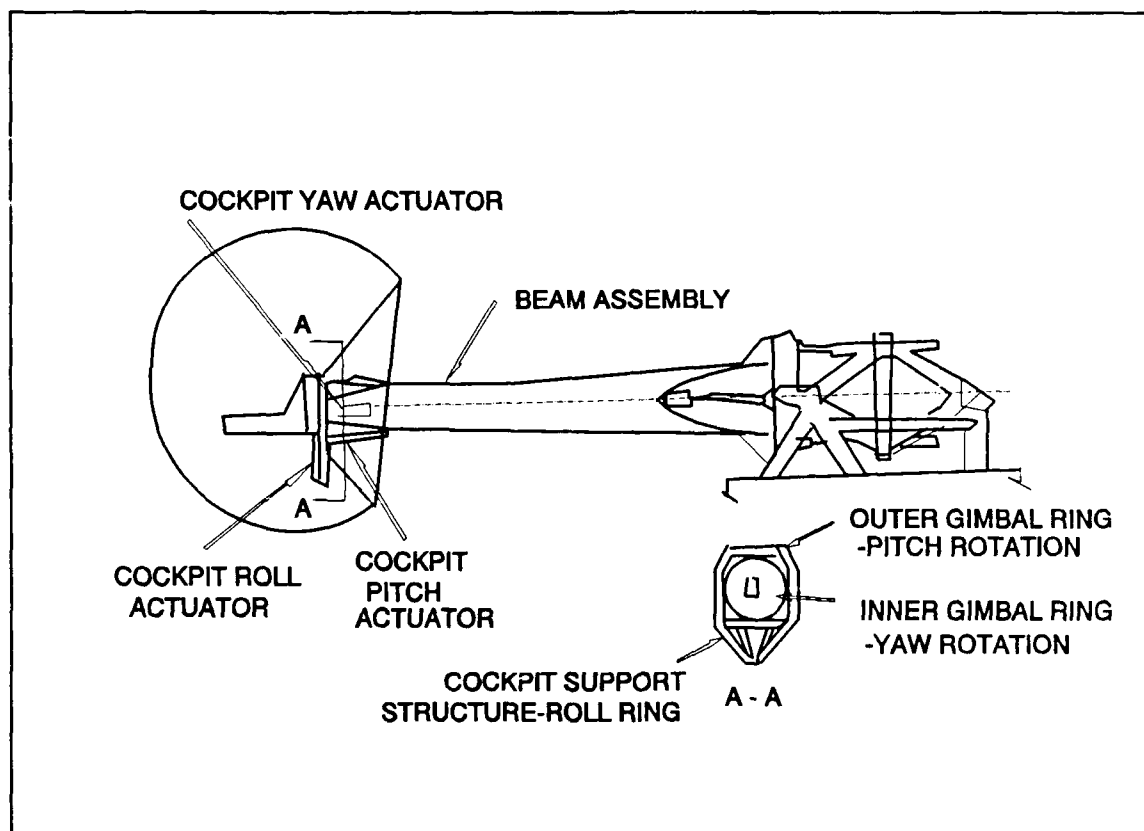


Figure 23. LAMARS Motion System

The LAMARS motion system shown in Figure 23 consists of a 30-foot long horizontal beam, gimballed and driven by hydraulic actuators at the rear end of the beam to provide ± 10 feet of both vertical and lateral motion to the cockpit. An

additional structure, the cockpit gimbal system, is mounted on the forward end of the beam and provides angular rotation (± 25 degrees in pitch, yaw, and roll motion) to the cockpit. The LAMARS motion system performance is summarized in Table D-1. Recent modifications, involving the elimination of a PACER minicomputer for motion washout computations and lead compensation in the motion drives, have produced exceptionally high quality (good phase relationship) motion cues.

Table 7. LAMARS Motion System Performance

AXIS	DISPLACEMENT	ACCEL.	VELOCITY	BANDWIDTH
VERTICAL	± 10 ft	± 3 gs	13 ft/sec	25 rad/sec
LATERAL	± 10 ft	± 1.65 gs	10 ft/sec	25 rad/sec
PITCH	$\pm 25^\circ$	± 400 %/sec ²	60 %/sec	25 rad/sec
YAW	$\pm 25^\circ$	± 200 %/sec ²	50 %/sec	25 rad/sec
ROLL	$\pm 25^\circ$	± 460 %/sec ²	60 %/sec	25 rad/sec

The transient motion cues provided by the LAMARS motion system are augmented by a g-suit which is programmed to provide positive, sustained cuing for load factor conditions above 1g."[5:11-14]

Appendix E: Data Reduction

Sustained turn performance data were reduced using the USAFTPS PDP 11/84 computer. Load factor, indicated airspeed, and fuel used were recorded by hand during the stabilized turn FTT.

All other data reduction was performed using IBM compatible personal computers. The data was downloaded using the USAFTPS PDP 11/84. After converting to engineering units, the data were transferred to the PC via the USAFTPS local area network. Lotus 123^(TM) and QuattroPro^(TM) were the software packages used for the remaining data reduction.

Time histories of indicated airspeed and load factor were recorded using the DAS during the lift limit line FTT. Load factor was standardized to a weight of 8800 pounds using a weight ratio:

$$n_{std} = n_{test} \left(\frac{W_{test}}{W_{std}} \right)$$

where: n = load factor
 W = weight

Non-steady state turn rate was calculated from pitch and yaw rates through Euler angle transformations using the following equation:

$$\dot{\Psi} = \frac{Q \sin \Phi + R \cos \Phi}{\cos \Theta}$$

where: $\dot{\Psi}$ = turn rate Q = pitch rate
 Φ = bank angle R = yaw rate
 Θ = pitch angle

Total heading change was calculated by integrating turn rate using this rectangular scheme:

$$\Psi = \sum_{n=1}^z \dot{\Psi}_{n+1} (t_{n+1} - t_n)$$

where: Ψ = heading change
 t = elapsed time
 z = last line of interest in the time history.

Appendix F: Time History Plots

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

2.0 g Snatch
20,000 ft. H_c
8540 lbs. G.W.
25.5% MAC c.g.

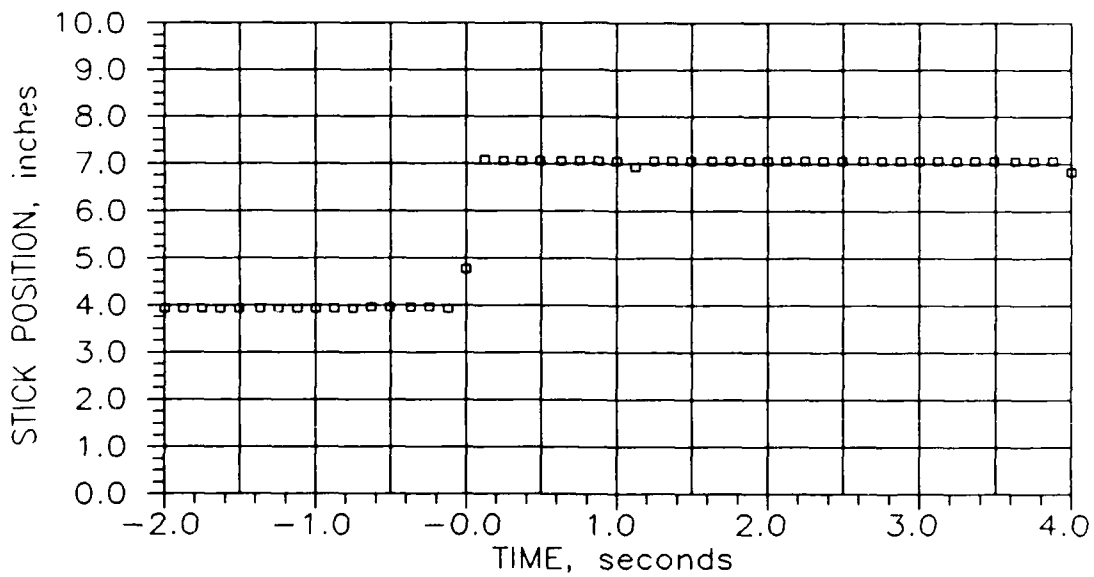
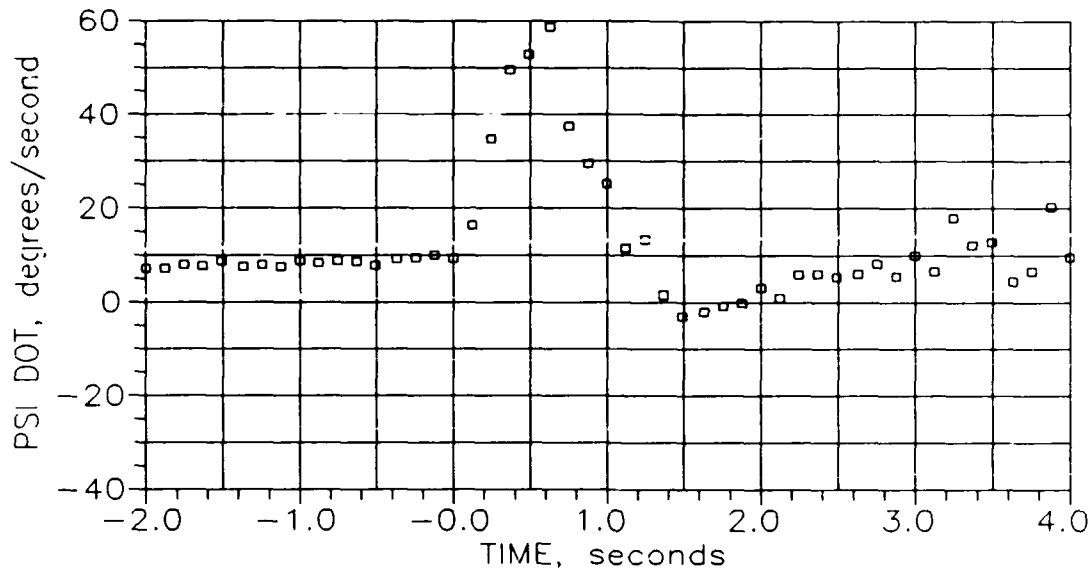


Figure F-1. Typical 2.0 g Angular Reserve Results (Sheet 1 of 2)

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

2.0 g Snatch
20,000 ft. H_c
8540 lbs. G.W.
25.5% MAC c.g.

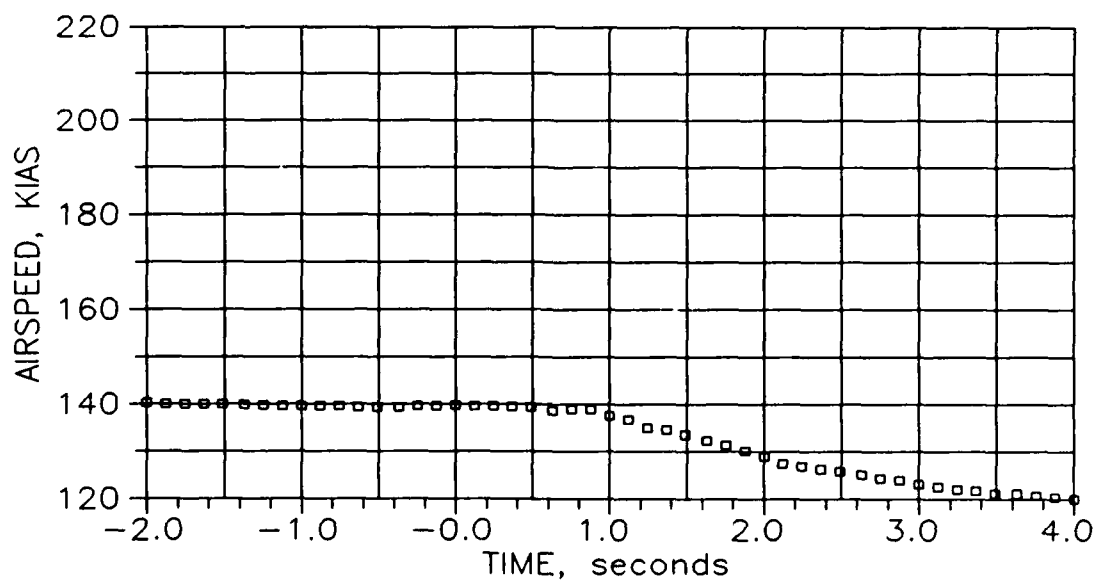
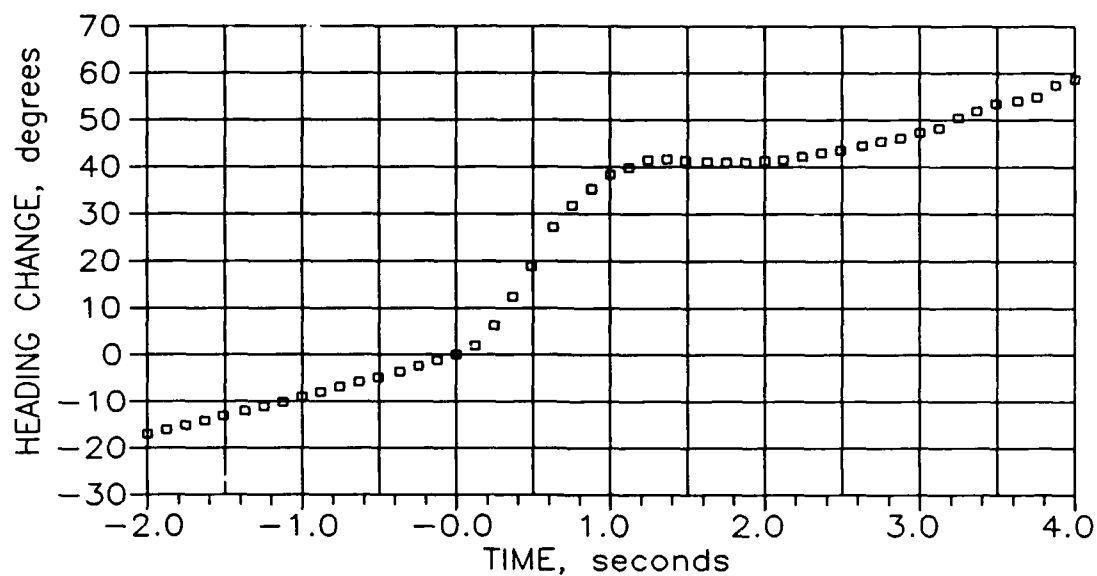


Figure F-1. Typical 2.0 g Angular Reserve Results (Sheet 2 of 2)

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

2.5 g Snatch
20,000 ft. H_c
8960 lbs. G.W.
25.7% MAC c.g.

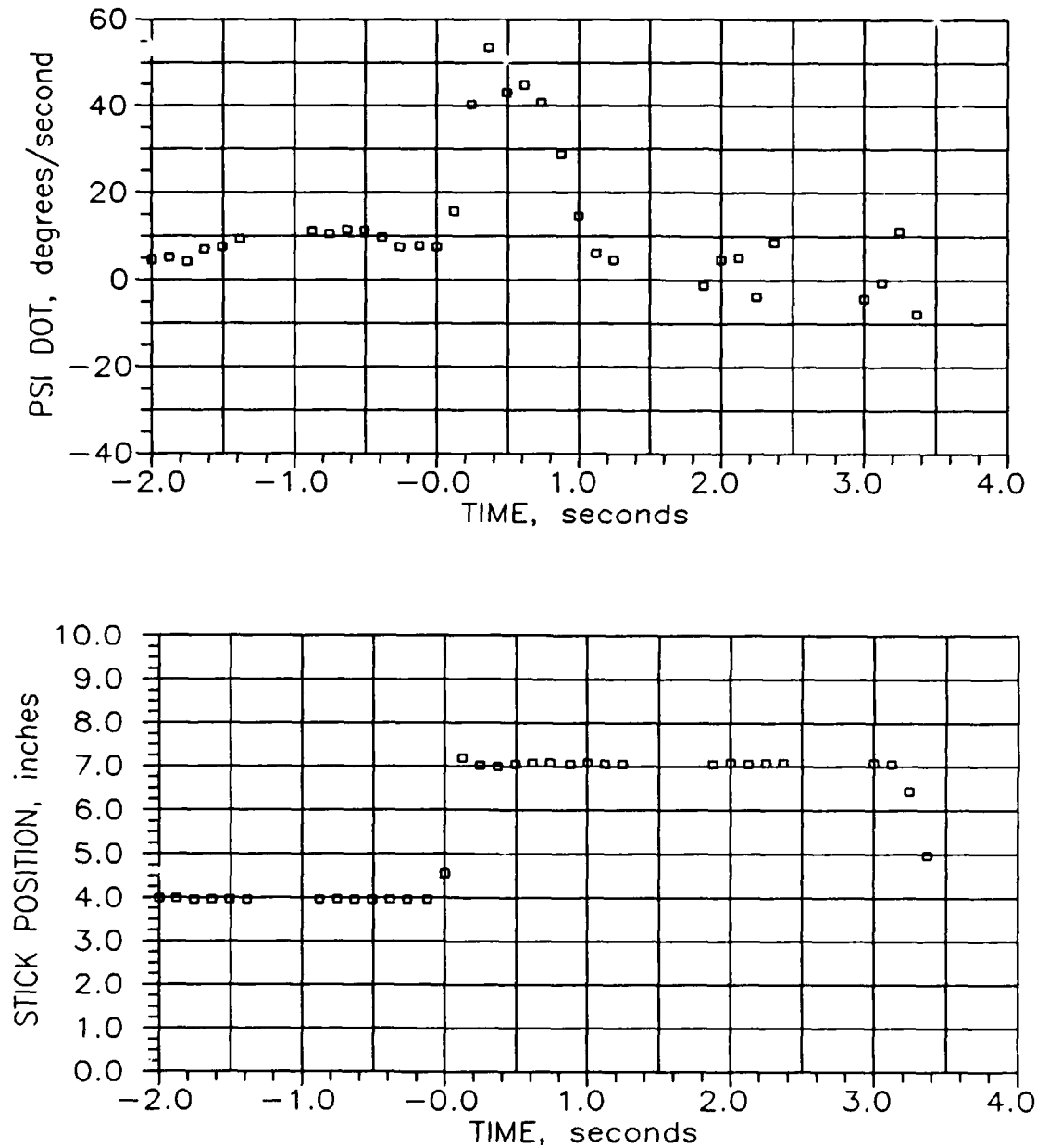


Figure F-2. Typical 2.5 g Angular Reserve Results (Sheet 1 of 2)

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

2.5 g Snatch
20,000 ft. H_c
8960 lbs. G.W.
25.7% MAC c.g.

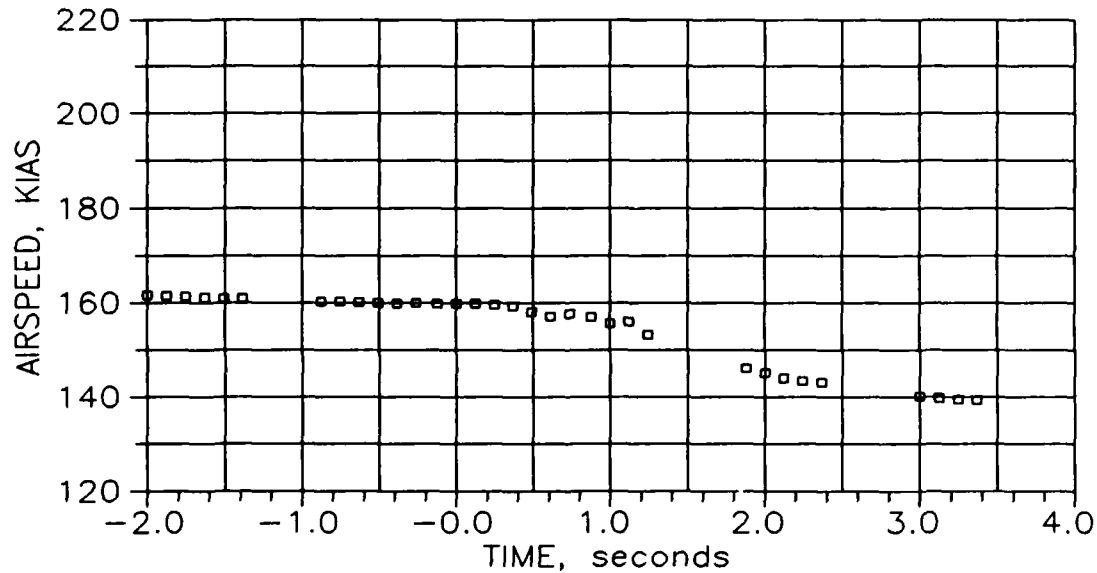
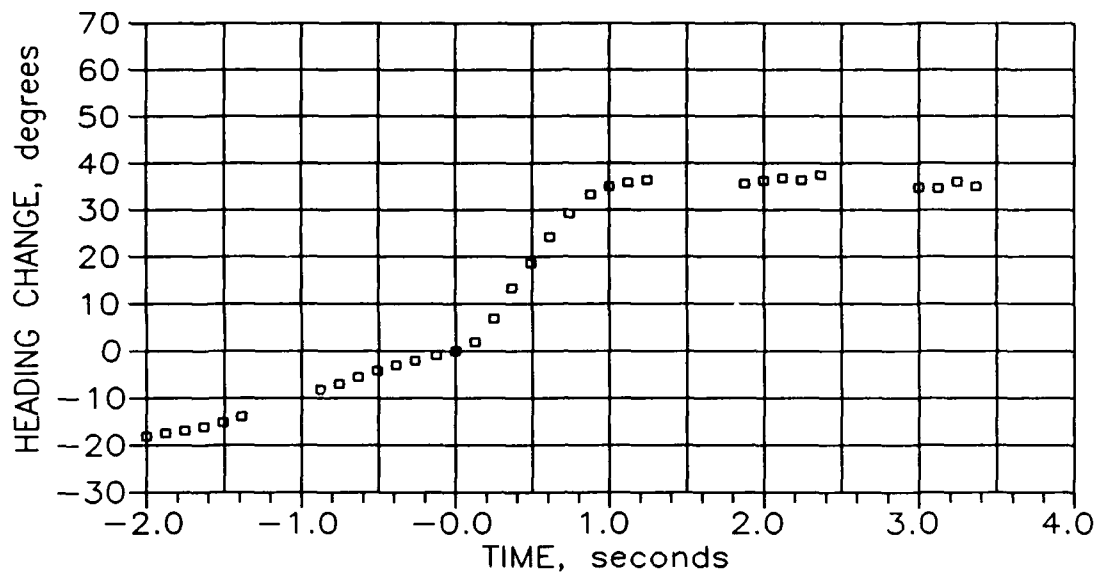


Figure F-2. Typical 2.5 g Angular Reserve Results (Sheet 2 of 2)

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

3.0 g Snatch
20,000 ft. H_c
7850 lbs. G.W.
25.4% MAC c.g.

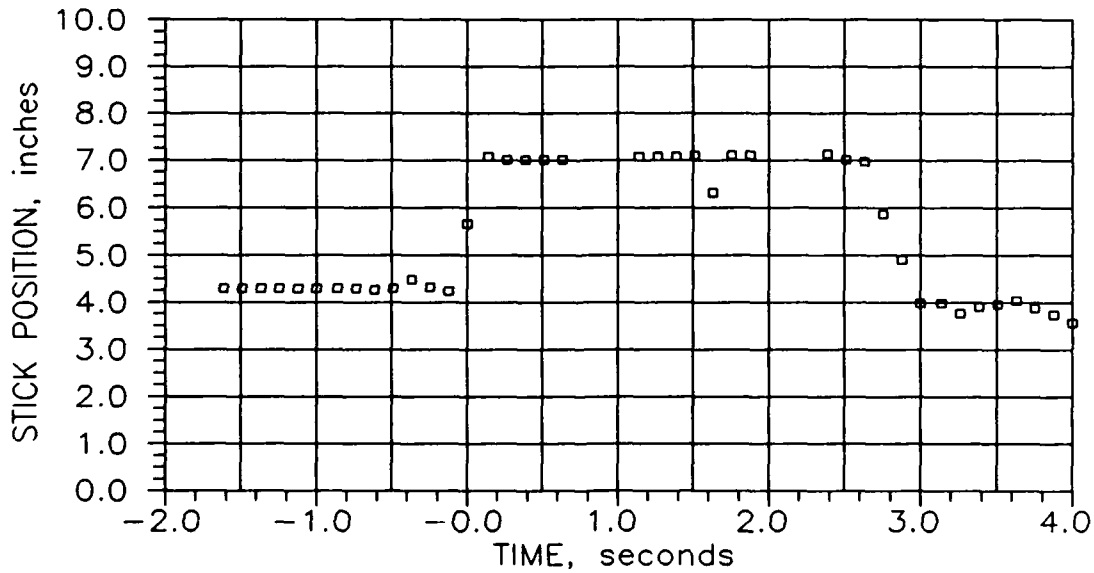
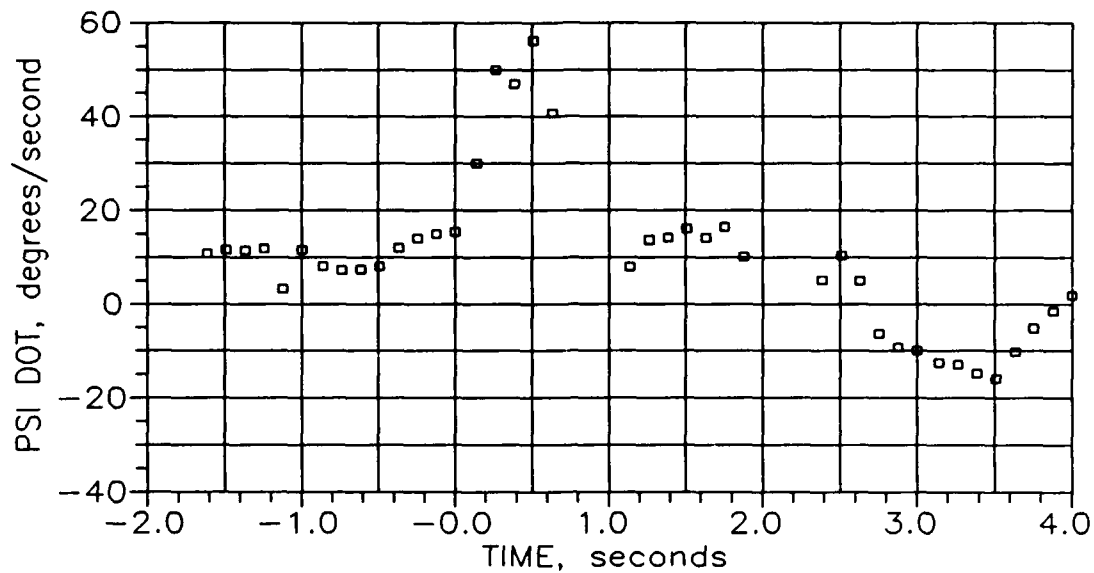


Figure F-3. Typical 3.0 g Angular Reserve Results (Sheet 1 of 2)

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

3.0 g Snatch
20,000 ft. H^c
7850 lbs. G.W.
25.4% MAC c.g.

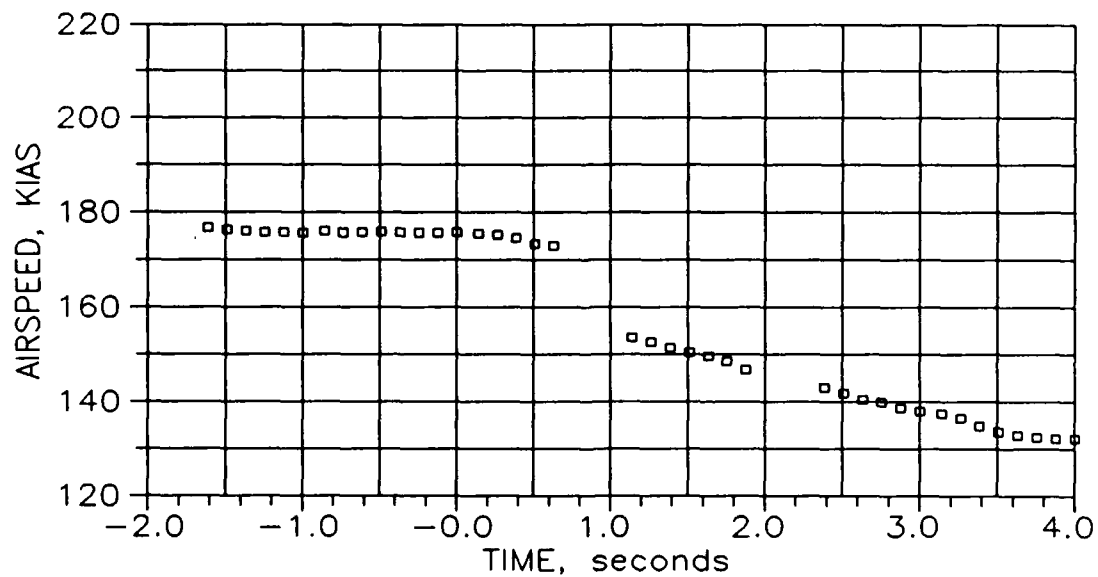
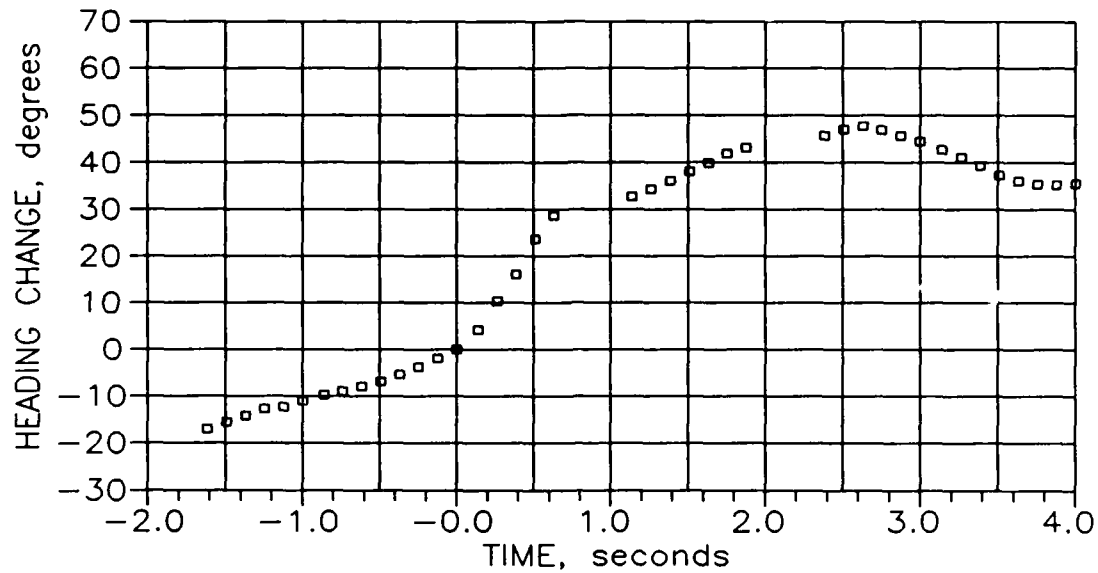


Figure F-3. Typical 3.0 g Angular Reserve Results (Sheet 2 of 2)

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

3.5 g Snatch
20,000 ft. H_c
8120 lbs. G.W.
25.5% MAC c.g.

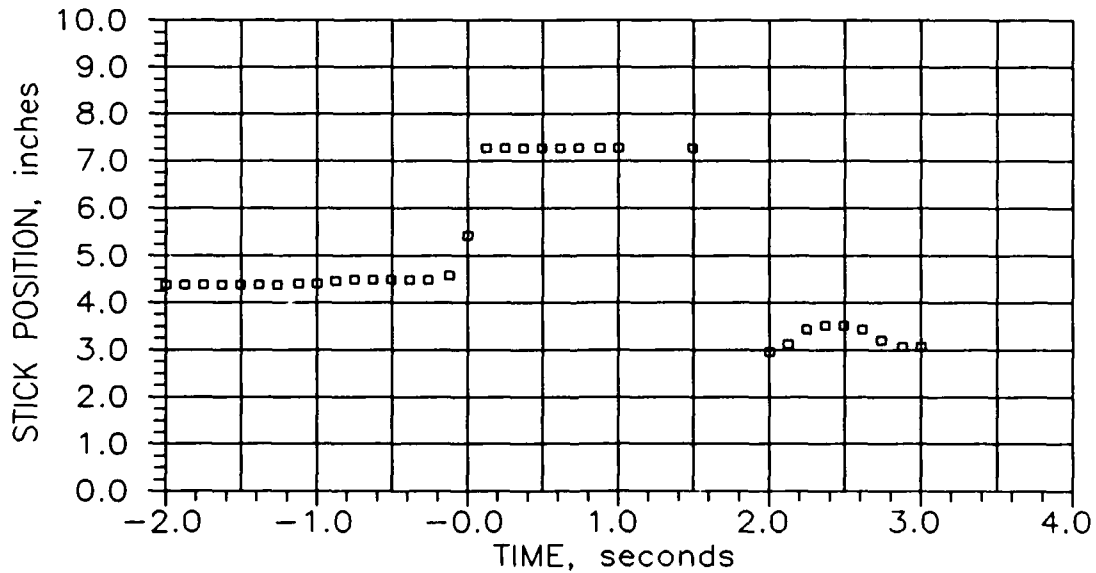
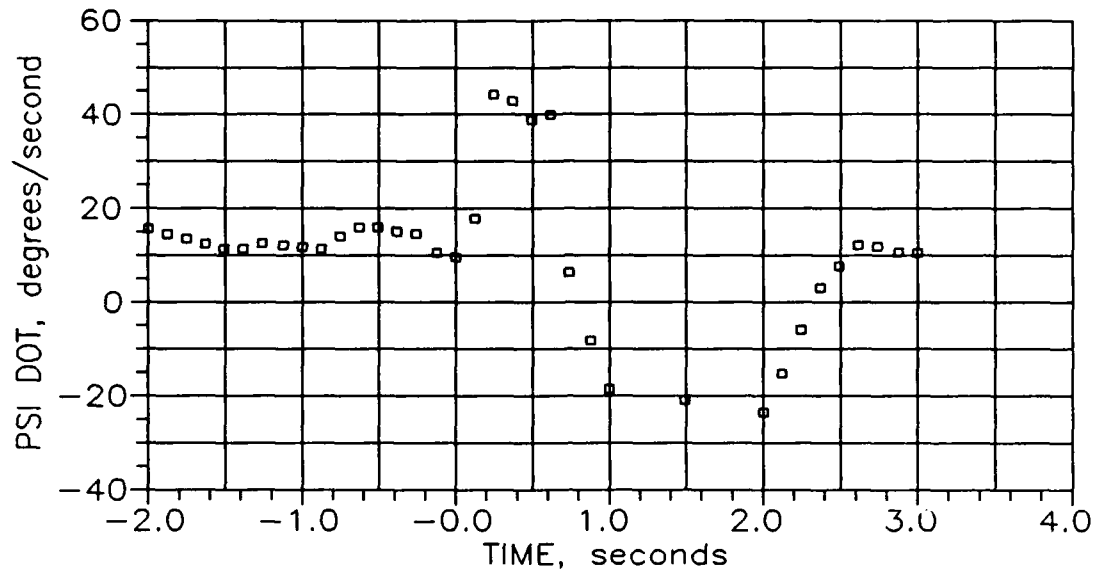


Figure F-4. Typical 3.5 g Angular Reserve Results (Sheet 1 of 2)

A-37B S/N 73-1090
19 Sep 90
Left Turns Are Positive
JP-4

3.5 g Snatch
20,000 ft. H_c
8120 lbs. G.W.
25.5% MAC c.g.

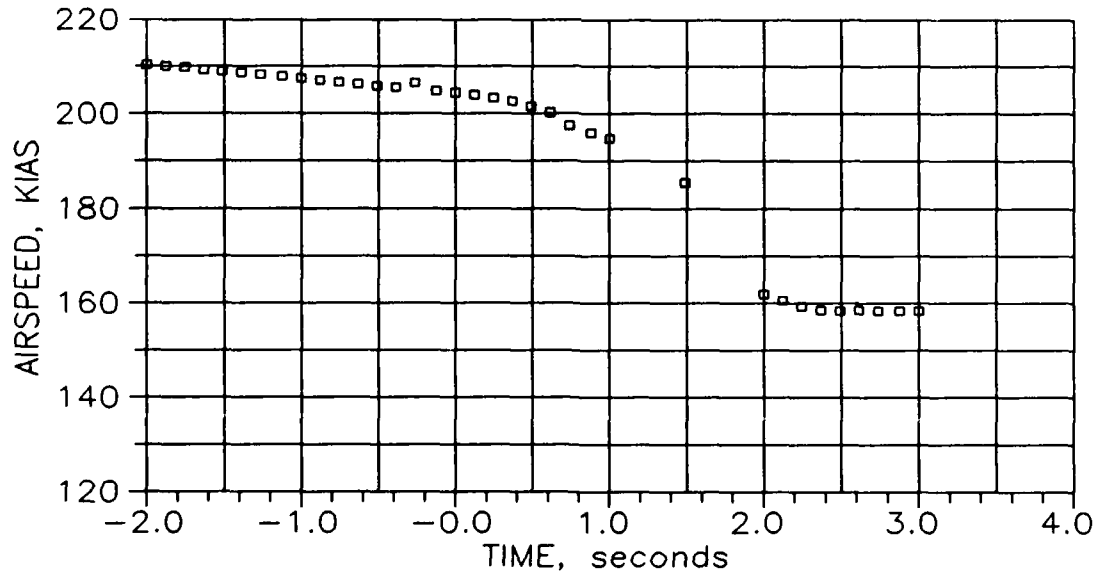
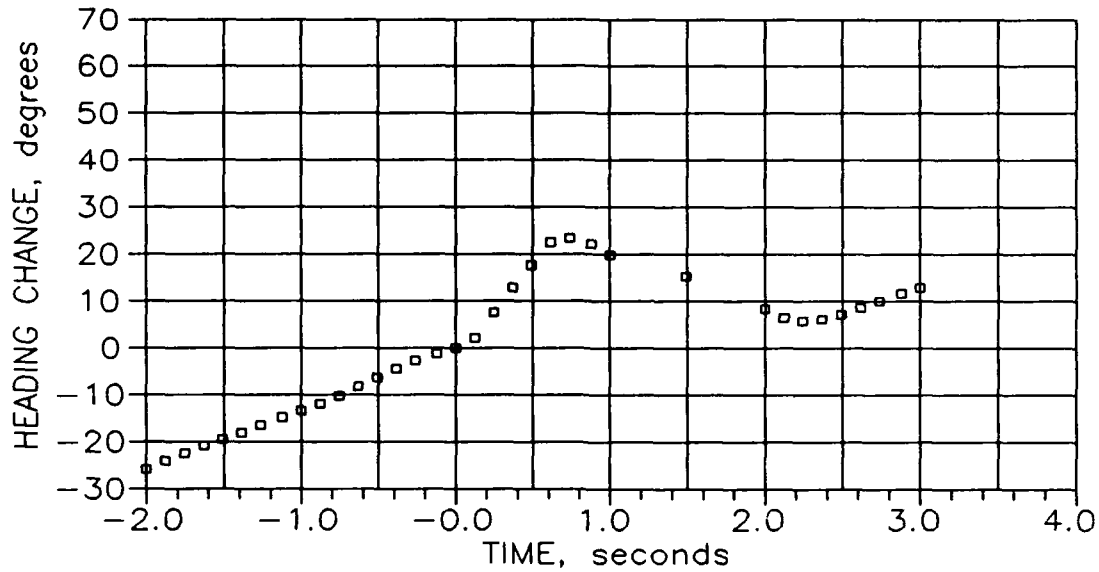


Figure F-4. Typical 3.5 g Angular Reserve Results (Sheet 2 of 2)

Vita

Captain William R. Langdon was born on 31 August 1958 in Phoenix, Arizona. He graduated from high school in South Bend, Indiana, in 1976 and attended Arizona State University, from which he received the degree of Bachelor of Science in Aerospace Engineering in 1981. Upon graduation, he received a commission in the USAF through the ROTC program. Immediately after graduation Captain Langdon attended pilot training in Columbus, Mississippi. After receiving his wings, he qualified in the F-16 and was stationed at Torrejon Air Base, Spain. Following this three year tour he was reassigned to Homestead AFB, Florida in the F-16 and remained there until entry into the Air Force Institute of Technology/Test Pilot School Program in August 1988. Captain Langdon is a graduate of the USAF Test Pilot School and has accumulated over 1700 total hours of flying time in over 25 different aircraft. He has accumulated over 1350 hours in the F-16A aircraft.

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